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PB80-102304

Lake and Reservoir Classification Systems

(U.S.) Corvallis Environmental Research Lab, OR

Jul 79

United States
Environmental Protection
Agency

Environmental Research
Laboratory
Corvallis OR 97330

EPA-600/3-79-074
July 1979

PB80-102304

Research and Development

EPA

Lake and Reservoir Classification Systems

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TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA-600/3-79-074

2.

3. RECIPIENT'S ACCESSION NO.
PB80-102304

4. TITLE AND SUBTITLE
Lake and Reservoir Classification Systems

5. REPORT DATE
July 1979 issuing date

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Thomas E. Maloney (editor)

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Environmental Research Laboratory--Corvallis
Office of Research and Development
U.S. Environmental Protection Agency
Corvallis, Oregon 97330

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS
same

13. TYPE OF REPORT AND PERIOD COVERED
final

14. SPONSORING AGENCY CODE
EPA/600/02

15. SUPPLEMENTARY NOTES

16. ABSTRACT

This publication contains a series of articles dealing with the trophic classification of lakes and reservoirs. These articles are concerned with the history of lake and reservoir classification systems and their present day use.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
lake restoration eutrophication reservoirs lakes water pollution		06/F

18. DISTRIBUTION STATEMENT
Release to Public

19. SECURITY CLASS *(This Report)*
Unclassified

20. SECURITY CLASS *(This page)*
Unclassified

21. NO. OF PAGES
248

22. PRICE
PC A11
MF A01

EPA-600/3-79-074
July 1979

LAKE AND RESERVOIR CLASSIFICATION SYSTEMS

Editor

Thomas E. Maloney
Freshwater Division
Corvallis Environmental Research Laboratory
Corvallis, Oregon 97330

CORVALLIS ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CORVALLIS, OREGON 97330

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FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory (CERL).

The primary mission of the Corvallis Laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects and control of pollutants in lake and stream systems; and the development of predictive models on the movement of pollutants in the biosphere.

This report contains a series of articles dealing with the trophic classification of lakes and reservoirs. The papers discuss the history of these systems and their present day use.

James C. McCarty
Acting Director, CERL

ABSTRACT

The problem of eutrophication of waters, initially recognized in only a few countries, was brought into the wide forum of the Organization for Economic Cooperation and Development (OECD) in 1967 to be dealt with by international cooperative action. The first stage was initiated in 1967 with an overall synthesis of existing knowledge concerning eutrophication. The second stage consisted of an overall evaluation of eutrophication control strategies, taking into account their effectiveness, cost and feasibility. In the early 1970's, when it was clear tnat only an intensive international effort could produce the needed progress in a reasonable time, a task force working on this problem came to the conclusion that the experience needed could only be obtained by the close coordination of Member countries. Therefore, in 1973 the OECD established a Cooperative Program on the Monitoring of Inland Waters for Eutrophication Control. Eighteen member countries became involved in four coordinated Regional Projects - Alpine, Nordic, Reservoirs and North American. Canada and the United State made up the latter.

The main objectives and expected results from the program were:

- to obtain a realistic scheme of the development of eutrophication, in extent and intensity in Member countries and to assess its spreading rate in various cases.
- to better understand the causes and conditions of its development, which is a prerequisite in taking adequate corrective measures against the responsible pollutants.
- to provide widely applicable guidelines and correlations which will permit the adoption of control measures of the right order, at the right time and the right place, thus making their cost/effectiveness far more satisfactory.

It was recognized early that there was a need to define more precisely the classical categories of oligo-, meso- and eutrophy. There is no clear delineation between trophic divisions and often different investigators would categorize the same body of water as having a different trophic state, depending to a great extent on their personal experience and on the area where they live. Recognizing the need for a more quantitative basis for classifying a lake, investigators turned their attention to developing a more quantitative framework based on correlating variables that reflect lake productivity which can be expressed in numerical terms.

This report contains the efforts of several of the United States investigators relating to their approaches to the classification of lakes in numerical terms and represents a part of the United States contribution to the North American portion of the OECD program.

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A REVIEW OF THE PHILOSOPHY AND CONSTRUCTION OF TROPHIC STATE INDICES

Robert E. Carlson

Department of Biological Sciences
Kent State University
Kent, Ohio 44242

INTRODUCTION

The concept of trophic state has been reviewed and discussed many times, yet the meaning of the concept is still not generally agreed upon. There are basically two aspects of the concept:

1. It has to do with either supply of nutrients coming into a lake or the concentration of these nutrients once in the lake. The larger the supply or concentration, the more eutrophic the lake will be.
2. It has to do with the biology of the lake, either its productivity or biological structure. The higher the productivity or standing crop, the more eutrophic the lake.

A compromise view is that trophic state is a multi-variate concept, incorporating aspects of both nutrients and biology. All three views have strong philosophical and historical arguments supporting their acceptance.

Interjected into this rather academic argument on the nature of trophic state is the pressing need to communicate with the public and its governments concerning the fate of rapidly eutrophying lakes and reservoirs. By communication I mean the ability to describe the present condition of the lake and its possible future condition in a simple, straight forward manner that can be understood easily by the layman. The trophic concept seems ideally suited for this purpose because in its most basic form "oligotrophic" could mean a clear lake with many desirable recreational characteristics, and "eutrophic" could mean a lake with dense algal or macrophyte communities. It is evident that these terms are already being extensively used in applied limnology. Clearly defined limits to oligotrophy and eutrophy become far more important when the terms are to be used as an applied tool rather than an academic discussion. Unambiguous limits must be set and relationships defined.

The need to be able to classify lakes has long been recognized. Often the various definitions of trophic state are so inclusive that to measure all aspects in the concept would be virtually impossible. To simplify the task of classification, often indicators or indices are used to determine the trophic state. Used singly or taken as a group average, these indicators have provided a means for rapid classification without resorting to complex and time-consuming analysis of all the components of the lake system.

There are fundamental differences as to how these indices are constructed depending on whether the trophic concept is perceived as a series of "types" or whether one perceives it as a point on a continuum. These perceptions of the trophic concept are illustrated in Figure 1.

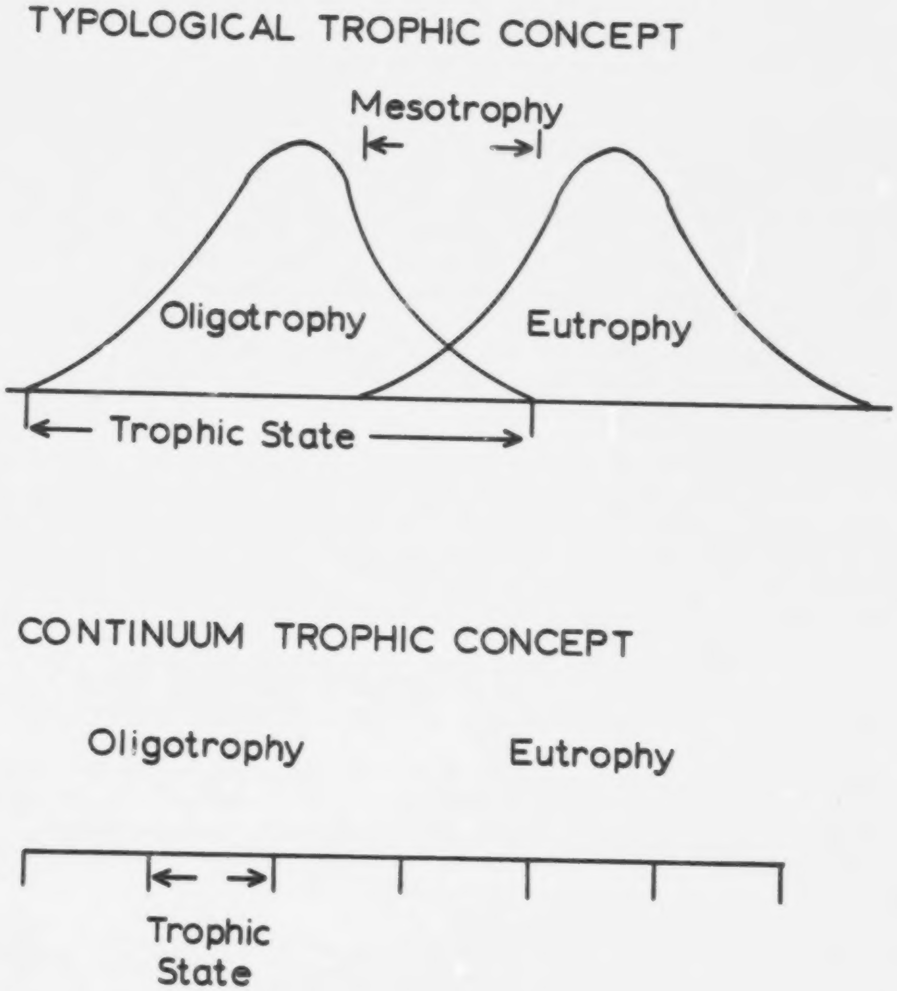
Naumann (1919) perceived lakes as falling into distinct classification groups or types of which oligotrophic and eutrophic were only two of many possible types. He apparently recognized that there was variation within the groups but that there were standard lake types about which these variants could be grouped. In many respects it is similar to the "type species" used in taxonomy. In this instance, although variation is acknowledged to exist among individuals of a species, there is a classification group (i.e., the species) into which these individuals are placed. It is considered that the variation among individuals of the same species is less than the difference among individuals of different species. The type specimen, the one or two individuals which serve as standards for characteristics of the species, is similar in concept to the standard attributes which are used to characterize eutrophic and oligotrophic lakes.

In contrast to this typological view, the trophic concept can be viewed as reflecting the attributes of a continuum Proponents of this view would argue that there are no distinct trophic "types" of oligotrophic and eutrophic, but a continuous and infinite variety of trophic possibilities ranging from those with the general attributes of oligotrophy to those with the general attributes of eutrophy. Trophic states are recognized along this continuum, but the number and location of the states are arbitrary.

Viewing the trophic concept as a series of types has resulted in limits being set to mark the range of values found for each state. Typological limits can often be recognized by their overlapping nature, as the range of values for a given trophic state may overlap considerably with the values of other states. Examples of limits of this type are given by Likens (1975) and Wetzel (1975). The problem with these indices is that they are of little help in classification. In the range of overlap the lake could be in either of two conditions, and the index cannot discriminate between the two. Instead of a single indicator, typological classification requires the use of several indicators in order to ascertain trophic status. If the proper criteria could be agreed upon, then some sort of cluster analysis could be used to facilitate classification. Shannon and Brezonik (1972) used such a technique to group 55 Florida lakes, and Sylvester and Hall (1974) used clustering techniques to develop a classification for Maine lakes.

The continuum trophic concept has also produced recommendations for trophic state limits, but these can be generally recognized because they are non-overlapping. The continuum concept results in other notable attributes:

1. As trophic states are considered to be arbitrary divisions of the trophic continuum, a limitation to two or three classification units (trophic states) seems unnecessary. Some lakes must be considered more eutrophic than others, and grouping them together results in a loss of information



TYPOLOGICAL TROPHIC CONCEPT
Mesotrophy
Oligotrophy
Eutrophy
Trophic State
CONTINUUM TROPHIC CONCEPT
Oligotrophy
Eutrophy
Trophic
State

Figure 1. An illustration of the differences between the typological and continuum views of the trophic state concept.

about the lakes. Because of this, sensitivity to change in trophic status becomes an important consideration. Two or three classification units are sensitive only to the grossest changes. Indices reflecting the continuum concept tend to recognize more nomenclatural classification groups (e.g., Vollenweider, 1968) or become numerical.

2. The processes or factors that are considered to be fundamental to the trophic concept must also be of a continuous rather than of a discontinuous sort. Indicators based on the presence or absence of certain attributes would be of little use, and the indicators used tend to be of a continuous nature. For example, orthograde vs. clinograde oxygen curves might be replaced with rate of hypolimnetic oxygen depletion, and *Tanytarsus* vs. *Chironomus* attributes might be replaced with indices of relative species abundance.

3. Unless all aspects of the concept of trophy are highly correlated and change along the trophic continuum at the same rate, lakes may still be classified differently depending on the criteria used. Solutions to this problem include the minimization of the number of criteria used in the classification, the correlation and transformation of all the criteria to the same basis, or the averaging by one technique or another of the disparate trophic values in order to obtain an average trophic state value.

This paper will largely deal with indices related to the continuum trophic concept. This emphasis is because of my own view that the continuum-type indices appear to be the most promising of producing a simple yet comprehensive measure of trophic status.

Five basic types of indices will be examined in this paper: typological indices, single-variable indices, multi-variable indices, external loading indices, and indices related to primary productivity, an often used trophic state criterion. The intent of the paper is to compare the construction and underlying assumptions of these indices and, where possible, describe quantitatively the relationships among the indices. It is hoped that this review can serve as a guide to persons in choosing an index to use or in constructing their own.

A SINGLE VARIABLE INDEX

Comparison and correlation of the many indices is difficult because each utilizes different variables for the determination of trophic state. Some indices use as many as five or six parameters while others use only one. Some use transparency, others use chlorophyll, while others use nutrient concentration. Even if one could compare the indices by using all the indices on the same series of lakes, the value of such a comparison is limited because there is no trophic standard to which the indices can be compared. In other words, one cannot answer the question, "Which index best reflects trophic state?", because the current standards are set up for only two states, eutrophic and oligotrophic, and there are few, if any, unambiguous trophic criteria even for these two states. In the absence of unambiguous trophic standards, the indices can only be compared amongst themselves.

The comparison was done using the index of Carlson (1977) as the basis for the comparison. This index is based on the amount of algal biomass present in the surface waters. The index consists of a numerical trophic scale which encompasses most lakes within values of zero to 110. The scale is based on a $\log_2$ transformation of the amount of algal biomass as measured by Secchi disk transparency. The result is a scale where each 10 units represents a doubling in algal biomass.

Other trophic parameters which are known to correlate with transparency (at present chlorophyll and total phosphorus) can be also used to calculate the index using regression equations which have also been transformed to $\log_2$ values in the same manner as was transparency. The index equations are shown in Table 1. In effect, any of the three parameters can be used independently to calculate the index value. Because of this, any other index that utilizes transparency, chlorophyll, or total phosphorus can be compared with the Carlson index.

According to Carlson (1977) the advantages of this numerical index are several. Its large number of trophic classes suggests potential for being sensitive to trophic change. The major trophic divisions are not arbitrary, however, as they represent doubling in algal biomass. The possibility of using any of three indices allows a parameter to be chosen that best fits the circumstances in a particular lake, as well as allowing the number of parameters measured to be minimized. The scale is absolute rather than relative. This means that the scale is not limited to lakes within the original data base. One end of the scale (0) is beyond all values reported in the literature. The other end is actually open-ended. By coincidence, however, few lakes have an index greater than 100, and the mean index value, at least in Minnesota lakes, appears to be between 40 and 50 (Shapiro, et al., 1975). As these trophic parameters have a skewed distribution, the logarithmic transformation apparently is responsible for the normal distribution observed.

Table 1. The equations used for calculating the trophic state index values of Carlson (1977).

Using Secchi disk transparency (m):

$$TSI = 60 - 14.41 \ln SD$$

Using Chlorophyll (mg/m^3):

$$TSI = 9.81 \ln Chl + 30.6$$

Using Total Phosphorus (mg/m^3):

$$TSI = 14.42 \ln TP + 4.15$$

As the index utilizes total phosphorus as one of the variables, it can be coupled with predictive nutrient loading equations, allowing prediction of changes in trophic state after changes in nutrient loading.

Brezonik (1976) criticized the Carlson index on several points. He considered that its simplicity actually detracted from its utility. He suggested that a multi-variate approach, which reflects a greater breadth of the trophic concept, is more useful for management purposes. He suggested that an averaging of the values might be more appropriate.

This concern with the breadth of the trophic concept that would be incorporated in an index is a major concern of this review. The Carlson index only measures open-water nutrient and biological variables. Brezonik and others have suggested that the trophic concept is multi-dimensional. The question of whether these multi-dimensional indices actually measure a greater proportion of the trophic concept will be discussed later. At this point in the discussion this index serves as an example of a single-variable index measuring one aspect of the trophic concept. Its advantage is its simplicity. Whether this simplicity is also a drawback will be discussed later.

THE CLASSIFICATION OF OLIGOTROPHY AND EUTROPHY

The terms "oligotrophic" and "eutrophic" are not only classificatory terms but are also terms describing certain attributes of lakes. As a description of attributes these terms essentially serve as two points that can be correlated against the trophic continuum.

In the same manner as transparency, total phosphorus, and chlorophyll have been shown to change in relation to the trophic continuum, the relationship of hypolimnetic oxygen concentration, phytoplankton species or fish species to the continuum could potentially be examined. At some point on the continuum these attributes will have values which would coincide with the traditional idea of oligotrophy, and at some other point the values will coincide with the traditional idea of eutrophy.

Many authors have given their opinions of what they consider to be the limits of oligotrophy and eutrophy in reference to various variables, both biological and chemical. In essence, they have been comparing single variables against their own conception of oligotrophy and eutrophy. By reversing this order of thought and utilizing the variables used in the Carlson index, it is possible to locate on that scale the limits of oligotrophy and eutrophy.

The trophic limits for values of total phosphorus, chlorophyll, and transparency that have been suggested by several authors are given in Table 2. The corresponding Carlson trophic state index (TSI) values are also given. The upper limits suggested for oligotrophy and the lower limits suggested for eutrophy are remarkably similar among the various authors. The similarity suggests that the changes in trophy are distinct enough that they can be recognized consistently. The mean TSI value for the upper limit to oligotrophy is 41 with a standard deviation of 5.75 while the mean TSI value for the lower limits of eutrophy is 51 with a standard deviation of 7.61. This means that the two most identifiable lake types are separated by only a single doubling in the amount of algal biomass in the lake which is brought about by a doubling in phosphorus concentration in the open water.

Of the whole range of possible locations for these two disparate trophic types, they are located within one doubling of algal biomass. How could all these changes take place with such a small change? Several possibilities are possible.

1. To some extent the average trophic limits may misrepresent the changes in individual lakes. For any given lake the changes in trophy may take several doublings of biomass to effect the change from attributes of oligotrophy to eutrophy.

TABLE 2 A comparison of the trophic limits to oligotrophy and eutrophy as suggested by several authors. The data is transformed using the index of Carlson (1977) to provide a uniform basis for comparison.

Author, Parameter	OLIGOTROPHIC	OLIGO-MESOTROPHIC	MESOTROPHIC	MESO-EUTROPHIC	EUTROPHIC
Sakamota (1966 a,b)					
Chlorophyll	0.3-2.5		1-15		5-140
TSI	(19-40)		(31-57)		(46-79)
Total Phosphorus	2-20		10-30		10-90
TSI	(14-47)		(37-53)		(37-69)
Vollenweider (1965)					
Total Phosphorus	<10	10-20	20-50	50-100	>100
TSI	<37	(37-47)	(47-61)	(61-71)	(>71)
Vollenweider (1968)					
Total Phosphorus	5	5-10		10-30	30-100
TSI	(27)	(27-37)		(37-53)	(53-71)
Vollenweider (1976)					
Total Phosphorus	<10		10-20		>20
TSI	(<37)		(37-47)		(>47)
Wetzel (1975)					
Chlorophyll	0.3-3		2-15		10-500
TSI	(19-41)		(37-57)		(53-92)
Brezonik (1976)					
Chlorophyll	1.3-3.2		1.8-9		3.5-93
TSI	(33-42)		(36-52)		(43-75)
Transparency	6.25-3.12		4.6-1		1.52-.22
TSI	(34-44)		(38-60)		(59-82)
Total Phosphorus	10-18		11-52		30-900
TSI	(37-46)		(39-61)		(53-102)
Vallentyne (1969)					
Chlorophyll	>5		5-10		>10
TSI	(46)		(46-53)		(>53)
Transparency	>6		3-6		<3
TSI	(<34)		34-44)		(>44)
Nat.Academy of Science (1972)					
Chlorophyll	<4		4-10		>10
TSI	(<44)		44-53)		(>53)
Dobson (1974)					
Chlorophyll	<4.3		4.3-8.8		>8.8
TSI	(<45)		(45-52)		(>52)
EPA Survey (1974)					
Chlorophyll	<7		7-12		>12
TSI	(50)		(50-55)		(>55)
Total Phosphorus	<10		10-20		>20
TSI	(<37)		(37-47)		(>47)
Transparency	>3.7		3.7-2.0		<2.0
TSI	(<41)		(41-50)		(>50)

2. The characteristics that observers use to delimit trophic state may be those that change suddenly around TSI values of 40-50. I doubt that trophic state is commonly decided by measuring the concentrations of phosphorus and chlorophyll. The changes in the lake are not so subtle as to require such sensitive techniques. Between TSI values of 40-50 transparency is halved from four to two meters. Such a change should be easily noticeable. It may be also that in this range many lakes become anaerobic in the hypolimnion. Such a noticeable change might strongly affect the determination of trophic state.

3. Rather than a statistical artifact or a subconscious weighting of trophic criteria, it may be that there are sudden, discontinuous events occurring as a lake eutrophies that rapidly shift it from one state to the other. The most obvious possibility is the loss of oxygen in the hypolimnion. As the bottom waters become anaerobic there are dramatic changes in fish species and bottom fauna. There are also large releases of phosphorus from the sediments as the iron complexes are reduced. These releases may change the hypolimnetic phosphorus concentration by ten-fold or more. Such a change could potentially change the phosphorus concentration of the epilimnion and thus change the algal biomass as was suggested by Mortimer (1941). If this were the mechanism for the rapid changing of trophic state, then there would be relatively few lakes having trophic index values between 40 and 50. However, Shapiro et al. (1975) found that, in Minnesota, of 80 lakes measured, the largest number was in the TSI 40-50 range.

Whatever the reason for the small distance on the trophic scale between oligotrophy and eutrophy, it emphasizes several aspects of the study of trophic state. The study of the changes in lakes with eutrophication has apparently been limited to only a small portion of the total trophic possibilities. Have we been too limited in our scope of investigations into trophic changes? Are there other changes, perhaps not so pronounced, that occur at other places in the trophic spectrum that remain undiscovered?

Is eutrophication (or oligotrophication) a discontinuous process? Do lakes suddenly change from oligotrophic to eutrophic? Is the change equally suddenly reversible? The evidence presented suggests that the study of the mesotrophic lake (TSI 40-50) may be extremely important to our understanding of lake dynamics. The answers to the above questions may have significant implications in lake management.

EXTERNAL CLASSIFICATION SYSTEMS

An important observation of Nauman (1927) was that lake types tended to correlate with the geological structure of the watershed. "General eutrophy" dominated in regions of Sweden that were flooded by the sea after the glacial period and in regions of calcareous moraines. In regions of primary rocks and moraines composed largely of primary rocks, "general oligotrophy" dominated. Although Nauman used this relationship between geology and trophy to emphasize the importance of the study of regional limnology, the relationship also emphasizes the importance of the watershed in the determination of trophic status of the lake.

Hutchinson (1969) suggested that instead of classifying water types, the watershed-lake-sediment system should be classified. A eutrophic system would be a system in which the total potential concentration of nutrients is high. It is possible, according to Hutchinson, that an oligotrophic lake might exist in a eutrophic system if the nutrients were tied up in a form or system component where they were unavailable to the organisms in the lake.

This approach to trophic classification has the advantage that it is independent of the many biotic and abiotic factors that may affect the general biological structure of the lake. In theory at least, it would free the trophic concept from both the historical and technical encumbrances that have frustrated the development of simple, uniform classificatory techniques. It also serves to broaden our scope to include the watershed as an important factor in influencing of the chemical and biological structure of lakes. It implies that the proper unit of study is the watershed rather than the lake alone (Odum, 1969).

This emphasis on the watershed-lake system is implicit in the recent work on nutrient loading models. The measurement of nutrient export from the watershed could be considered an index of the potential trophic status system of Hutchinson (1969). Beeton and Edmondson (1972) distinguish between oligotrophy and eutrophy of a lake by the amount of nutrients supplied by the watershed. They again regard supply as a better indicator of trophic status than internal measurements because of the uncertainty as to how the nutrients will be used once in the lake.

Specific nutrient loading (gm nutrient/m^2 of lake surface/year), proposed by Vollenweider (1968), has become a standard term for nutrient loading. The now-famous graphs of specific loading versus mean depth (Vollenweider, 1968), of loading versus mean depth divided by mean hydrologic residence time (Vollenweider, 1975), and mean inflow concentration versus hydrologic residence time (Vollenweider, 1976) have often been used to classify lakes.

It is sometimes bewildering why people would go to the effort and expense to construct a nutrient budget, place a single point on a graph, and then point out that the point's location on the graph definitely shows that the lake is eutrophic, when much simpler internal trophic standards are available.

Two reasons for the use of the graphical classification can be suggested. The graphs provide a recognized and quantitative method of external lake classification. The graphs are producing a predicted mean phosphorus concentration. This concentration is compared against trophic limits which have been previously established (10 and 20 mg/m^3 total phosphorus). The lakes then are actually being classified by the "potential" or predicted concentration. Internal factors, other than water residence time, that might modify that concentration are ignored.

A second possibility for the popularity of such graphs is that they provide a visual representation of the lake's trophic status in reference to the trophic limits of oligotrophy and eutrophy. The distance from those limits by that single point is an effective indicator of the degree of its trophic status. The graphs are an exceptionally effective method of communication, especially with laymen. In instances where lake restoration by nutrient income abatement is being proposed, it is possible to demonstrate the effect on trophic state of the predicted diversion.

In 1968, Vollenweider also set tentative limits between oligotrophy and eutrophy based on specific loading of 0.2-0.5 gm total p/m^2/yr and of 5-10 gm total N/m^2/yr. Since then, the use of specific loading alone as an index or standard of trophic state has been criticized because it incorporates the effects of both nutrient and water loading (Kerekes, 1975; Dillon, 1975). Because of this, nutrient incomes consisting of low nutrient concentrations but high water inputs could have higher specific loading values than others having high nutrient values but low water discharge. An alternate term was introduced by Vollenweider (1975) to adjust for this hydrologic interference. Termed "average inflow concentration," the term is actually specific nutrient loading (L_s) divided by the specific hydrologic discharge from the lake (q_s). Vollenweider's average inflow concentration is not the actual incoming concentration as q_s does not include the water loss by evaporation. Carlson (1977) suggested that the actual mean incoming concentration (C_I) would be useful as a trophic index. Mean incoming concentration is the concentration of water as it enters the lake and is defined as

$$C_I = J/Q_I$$

Where:

J = the total nutrient loading (Kg/time)

Q_I = the total inflow of water (m^3/time)

This formulation weighs the actual nutrient concentration from each source by its relative contribution of water to the total discharge entering the lake.

The average inflow concentration of Vollenweider (1975) is related to C_I by the fraction of water lost from the lake by evaporation.

$$L_s/q_s = C_I \ (Q_I/Q_o)$$

Where:

Q_o = the total loss of water by means other than evaporation

Mean incoming concentration (C_I) can be used as an external index of trophic state in several ways:

1. It can be used to classify individual streams and rivers in order to provide a regional aspect to the trophic nature of watersheds.

2. It can be used instead of export values to classify the effect of different land uses on nutrient release. Export values, expressed as Kg nutrient/area/time suffer the same drawback as specific loading, i.e., they incorporate both nutrient and a water loading into a single value. It may be that although runoff may vary regionally, that there is considerably less variation in nutrient concentration for a specific land use. If this were the case, then changes in a watershed's C_I could be predicted based on estimated changes in land use.

3. Mean incoming concentration can also be used to index the concentration of nutrients entering a specific body of water. As changes in the concentration of nutrients entering lakes are a primary cause of eutrophication, C_I serves as the direct index of these changes.

A major advantage of external trophic classification by means of incoming concentration is that it could classify a stream, river, lake, reservoir, or bog. The system could be used in areas where standing bodies of water are non-existent, yet where the condition of rivers is a major concern.

External classification does have several disadvantages. The word "nutrient" includes a large number of elements, any one of which could potentially be classified. Separate classifications for all the major and minor nutrients is clearly impossible. At present, classification appears to be based on the concept of the limiting nutrient. Phosphorus is often used in loading models because it is thought to often be the limiting nutrient. However, Castle Lake, California is limited by molybdenum (Goldman, 1960) and Clear Lake, California is limited by nitrogen (Horne and Goldman, 1972). Would separate classifications be made up for each lake limited by different elements? Implied in the use of the limiting nutrient concept is knowledge that the biological structure within the lake is limited by a nutrient. Thus, measurements must be made within the body of water prior to classification, a clear violation of the intent of external classification.

It may be that Hutchinson's trophic system can be no better defined nor more easily measured than the trophic concepts based on within-lake measurements. If this is so, then it might be that the classification of the watershed system would also require the use of an index incorporating only a few "indicator" nutrients. The graphs of Vollenweider (1968, 1975, 1976) or the various nutrient loading models that have been proposed might act as external indices once suitable criteria are established within the lake (such as Vollenweider's use of 10 and 20 mg/m^3 of total phosphorus). The internal nutrient concentration estimated by the use of the graphs or nutrient models could be used as a basis for classification regardless of the actual concentration found in the lake. This method would have the advantage suggested by Hutchinson (1969) and Beeton and Edmondson (1972) of disregarding the internal dynamics of the lake and concentrating on its "potential" trophic state. Such a classification system might be particularly useful in lakes deviating from the "normal" lakes considered in the establishment of the trophic criteria, i.e., those that are either not large, not deep, or not dominated by planktonic growth forms.

The advantage of the external classification is also its disadvantage; it does not classify the lake. Because of internal modifications, there may be large divergences between predicted trophic state and observed. If the predicted concentration gives a mesotrophic classification, yet because of internal loading there are extensive beds of macrophytes changing the actual lake condition to eutrophic, of what use is the external classification to the cottage owner?

External nutrient loading is presently a viable method for trophic classification. The models available use total phosphorus as the sole parameter for classification, and classification is based on a comparison of the predicted internal nutrient concentration to internal phosphorus concentrations. The most developed system of this kind is the graphical classification of Vollenweider (1976). The advantages of such a system are:

1. It emphasizes the importance of external factors on the internal dynamics of a lake.

2. It rapidly indexes the effects of changes in land use or nutrient diversion.

3. It avoids problems of the fate of nutrients once they enter the lake.

The disadvantages of the system are:

1. It assumes that nutrients, most often, only phosphorus, are the limiting factor in the lake. Other possibilities such as light or temperature are ignored.
2. It is based on a specific nutrient loading model which assumes, among other things, a completely mixed basin, a constant sedimentation rate, no sediment nutrient release, and equal biological activity for all forms of incoming phosphorus. The model used, however, could be modified to suit the particular lake that was to be classified.
3. The system may not be sensitive to the actual conditions within the lake, and therefore, would make it difficult to use as a tool in classification with the use-oriented public.
4. The system requires a great deal of data over at least a year, making it a very expensive classification system.

PRIMARY PRODUCTIVITY AS A TROPHIC INDEX

Productivity, especially primary productivity, has been the fundamental measurement and index of trophic state since its conception by Naumann in 1919. Oligotrophic lakes are defined as having low productivity and eutrophic lakes by high productivity. Rodhe (1969) defines trophy of a lake as "the intensity and kind of its supply of organic matter."

Primary productivity is commonly reported on an areal basis (gm/m^2) and on either a daily or annual basis. The range of values for daily areal productivity during the summer range from less than 35 mg/m^2/day in Char Lake, N. W. T. (Kalff and Welch, 1974) to values higher than 8000 mg/m^2/day (Vollenweider, 1968). Several ranges of areal productivities have been established for oligotrophic and eutrophic lakes (Table 3).

Although for theoretical reasons primary productivity may appear to be the ideal standard for trophic state determinations (Vollenweider, 1968), it has been under increasing criticism for a number of reasons. These reasons include problems of technique, insensitivity, and non-agreement with other trophic parameters.

Two common methods are employed to measure primary productivity. The measurement of oxygen released during photosynthesis is a relatively simple technique requiring little in the way of equipment or expertise. However, the technique is inaccurate at low productivities where the changes in O_2 are small. Increasing the incubation times to increase the total oxygen change also allows time for the growth of bacterial populations which will affect the result. The alternative to the oxygen technique employs the ^{14}C isotope. The technique is extremely sensitive and can be used in any type of lake. However, it requires the use of very expensive equipment and a relatively sophisticated operator both for reasons of safety and accuracy. The meaning of the results is also disputed, although the values are thought to approximate net photosynthesis. There is also criticism of results in which the possibility of excretion of labeled carbon products is not included (Vollenweider, 1969).

Insensitivity to trophic change and non-correlation with other trophic parameters may potentially be the criticism that will finally effect the greatest change in productivity measurements as they are now reported. Vollenweider (1968) states that although the high and low ends of the trophic spectrum are adequately predicted by primary productivity, in the intermediate range (100-1000 mgC/m^2/d) there are found inconsistencies between the trophic states predicted by primary productivity and that predicted by other trophic parameters. Fee (1973), for example, found that areal productivity measurements on offshore Lake Michigan samples indicated that the lake was eutrophic, contrary to all indications by other criteria.

Table 3. Suggested trophic limits based on areal primary productivity.

Trophic State	Areal Productivity ($mgC/m^2/day$)		
	Rodhe, 1969	Likens, 1975	Wetzel, 1975
Ultraoligotrophic	-	<50	<50
Oligotrophic	30 - 100	50 - 300	50 - 300
Mesotrophic	-	250 - 1000	250 - 1000'
Eutrophic	300 - 1000	600 - 8000	>1000
Hypereutrophic	1500 - 3000		

The reason for these inconsistencies in the mid-trophic ranges may not be because of real differences in the rate of incorporation of carbon by the algae but by factors not related to trophic status at all. It may be that what is considered to be changes in productivity with trophic state are no more than changes in the optical qualities of the water in which the measurements are taken.

Vollenweider (1960) presented the equation

$$\pi = F(i) \cdot \frac{1}{E} \cdot P_{opt}$$

Where:

π = integral photosynthesis (mg C/m^2/day)

$F(i)$ = a function of the photosynthetically active light

E = the attenuation coefficient of the light in water (1/m)

P_{opt} = productivity (mg C/m^3) at optimum light

The productivity at optimum light can be further divided into

$$P_{opt} = P_{max}\ C$$

Where:

P_{max} = the productivity per unit chlorophyll (mg carbon/mg Chl/day)

C = concentration of chlorophyll at the depth of optimum light (mg Chl/m^3)

Areal photosynthesis (π) is then a function of several factors, not all of which are related to algal biomass

$$\pi = F(i) \cdot \frac{1}{E} \cdot P_{max} \cdot C$$

The photosynthetic coefficient (P_{max}) or the maximum specific rate of photosynthesis or the assimilation number is known to vary with temperature (Schelske et al., 1974; Megard, 1972; Talling, 1966) and with nutrient depletion (Curl and Small, 1965; Thomas, 1970; Thomas and Dodson, 1972). Megard (1973) found that P_{max} was positively correlated with extractable cellular phosphorus. Although the range of values can be quite large, there is little evidence that the mean values are a function of trophic state. It appears that P_{max} is characteristic of the physiological state of the individual cell and is independent of the number of cells. Megard et al. (unpublished) considers a value of 50 mg C/mg Chl/day a "reasonable estimate of the mean value in lakes and oceans where temperatures are 20°C."

The vertical extinction coefficient (E) in effect decreases areal productivity as the coefficient increases. The coefficient can be subdivided into several components. Bannister (1974) divides it into the extinction of light by water and non-chlorophyll material (k_w) and extinction of light by chlorophyll (k_cC). The resulting term

$$E = k_w + k_cC$$

shows that extinction of light is not just a function of algae but of water also. If k_w is large in comparison to k_cC, then productivity/m^2 will decrease in a non-linear fashion (Megard, et al., unpublished) as a function of chlorophyll concentration. This effect on primary productivity is illustrated in Figure 2 assuming a P_{max} of 50.

The theoretical upper limit to productivity (Π_{max}) under a unit area is obtained when light is absorbed solely by chlorophyll (Bannister, 1974). It is approached in natural waters as light extinction by chlorophyll becomes large relative to the extinction of light by dissolved substances and water. This limit is in fact not a function of chlorophyll concentration but of the photosynthetic parameters F(i) and P_{max}, as the chlorophyll potentially could be widely distributed throughout the water column. Because of this independence of maximal areal productivity from chlorophyll concentration, large areal productivity values could be obtained in oligotrophic lakes as long as k_w were very small. Variations in k_w in oligotrophic and mesotrophic lakes may in fact be the cause of the wide differences in areal primary productivity reported in lakes of similar trophic status, as determined by other criteria.

Although the extinction coefficient of water and dissolved substances (k_w) varies at least three orders of magnitude in natural waters, much of the varience is a function of changes in trophic state. Megard (1972) suggested that the material included in k_w (dissolved color, suspended detritus, and zooplankton) may be related to variations in algal density. Using the data given in Tables 2 and 3 of Megard et al. (unpublished), it can be shown that k_w and chlorophyll are indeed correlated (Figure 3). This graph might imply a direct relationship between K_w and chlorophyll concentration as if either organic color is produced by the algae themselves or that K_w is actually measuring the non-chlorophyllous portions of the cells themselves. Megard et al. (unpublished) presented evidence that K_w was seasonally constant in a given lake and independent of the seasonal fluctuation in chlorophyll. This implies that both K_w and chlorophyll are both independently related

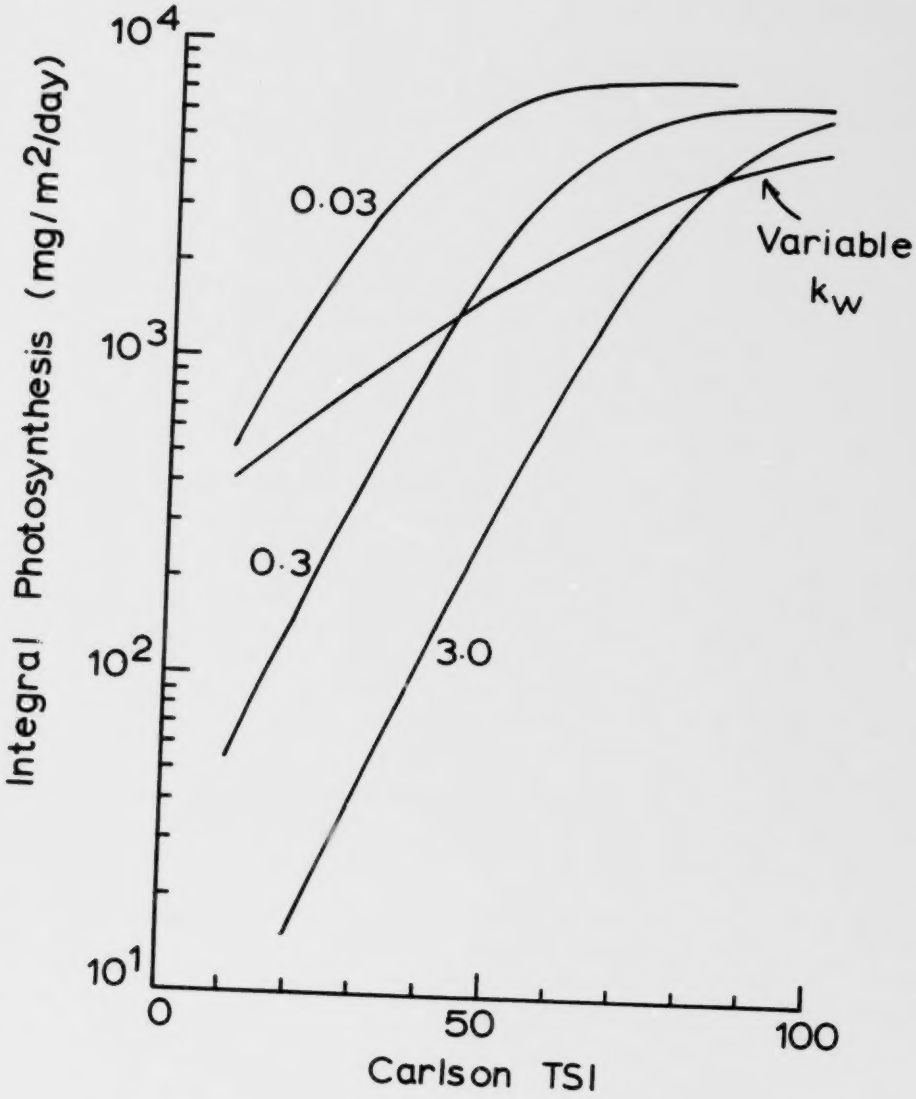


Figure 2. The relationship between trophic state as reflected by the Carlson index and integral photosynthesis (π). The curves represent K_w values of 0.03, 0.3, 3.0 and a K_w varying as a function of chlorophyll (see text).

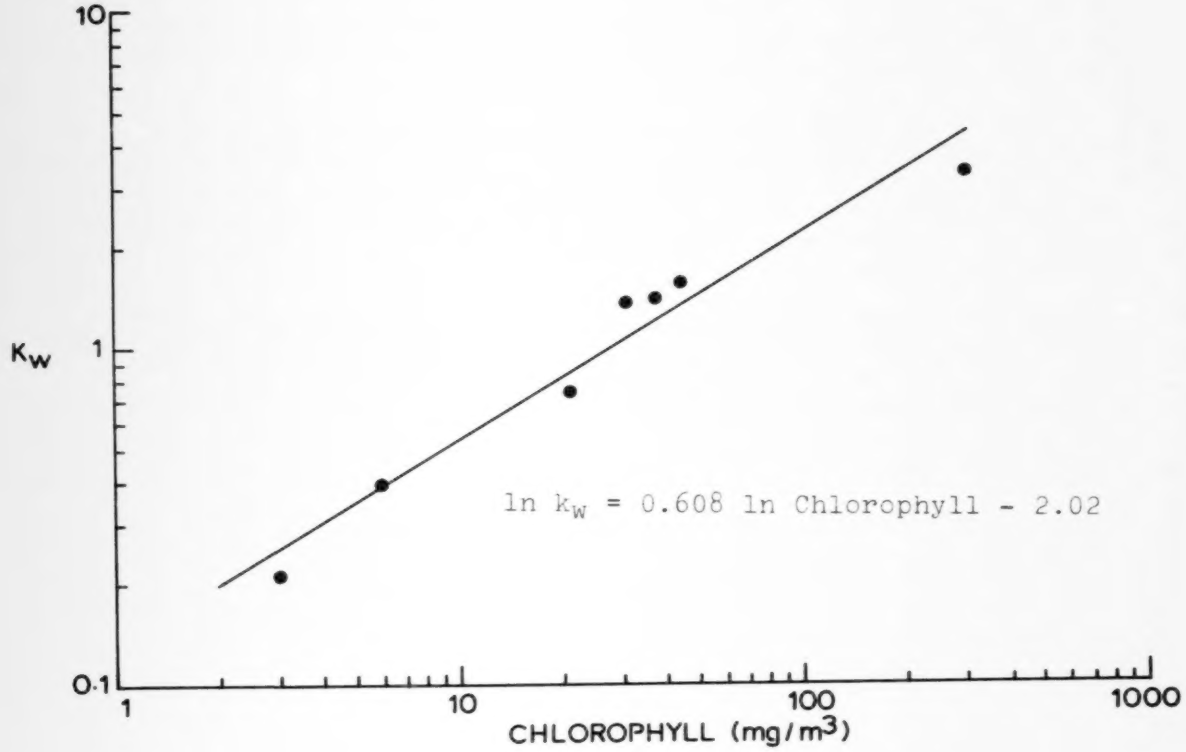


Figure 3. The relationship between extinction of light by non-chlorophyll substances (K_W) and chlorophyll.

to a third factor. Two possible suggestions for this unknown factor are (1) a possible relationship between phosphorus concentration and color in the incoming waters and (2) the contribution of color from the decaying organic matter in the sediments. At present, there is little data to support or refute either possibility.

The fact that K_w does vary as a function of chlorophyll does not produce any problems in the use of areal productivity as a trophic criterion. However, the indication that K_w and chlorophyll are not directly related suggests that an unknown amount of variation around the regression line may be possible. The darkly-stained waters of the otherwise oligotrophic dystrophic lakes may be the extreme of such variation. Differences in K_w between lakes of similar nutrient and algal biomass could produce widely different areal productivity values.

The problems of the insensitivity of areal productivity to trophic change have been recognized. Rodhe (1958) found that productivity per unit volume at the depth of optimal light (P_{opt}) was more sensitive to regional differences than integral productivity and suggested it might be used for the "biological" characterization of lakes.

Rodhe (1958) also presented a log-log graph of integral productivity (π) against volumetric productivity at optimal light (P_{opt}). There appears to be a good correlation between the two measurements. Using the equation:

$$\pi = z_i P_{opt}$$

the log form of the equation would be

$$\log \pi = \log z_i + b \log P_{opt}$$

Where:

$$z_i = \frac{F(i)}{E}$$

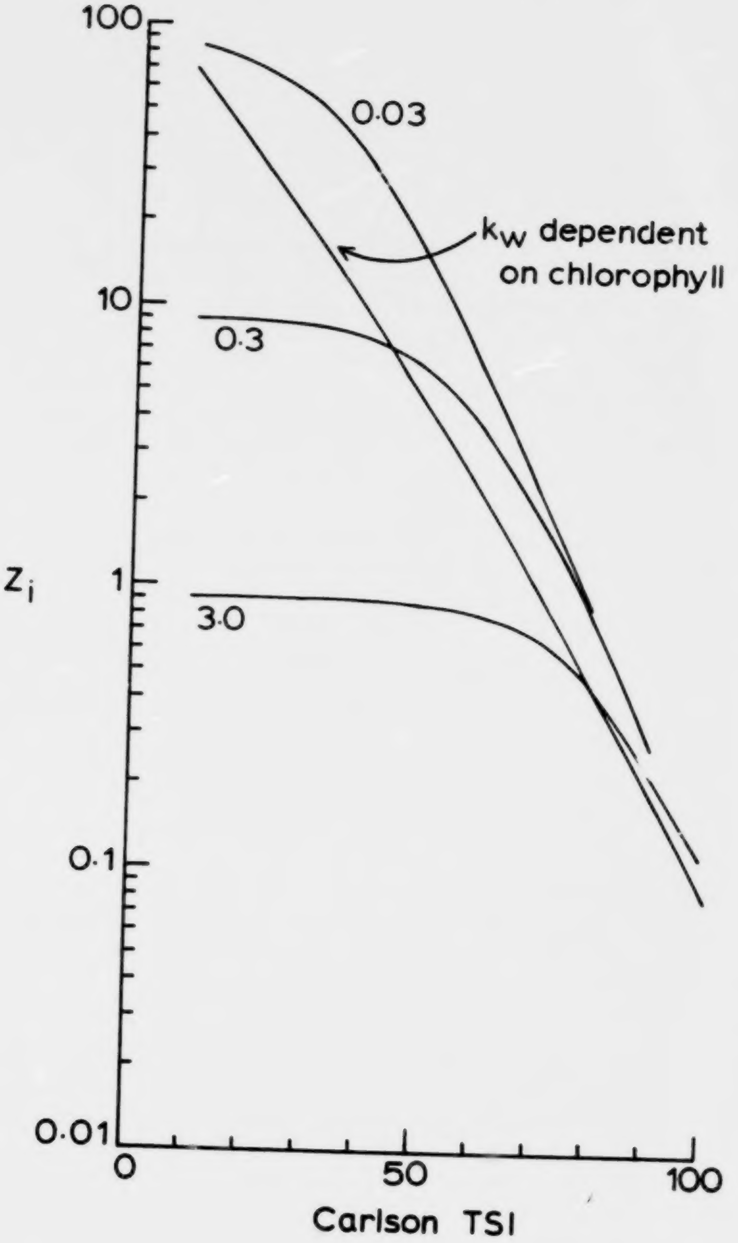


Figure 4. The relationship between Z_i and trophic state as reflected by the Carlson index. The curves represent the same K_w values described in Figure 2.

The logarithm of z_i would be the intercept, and b would be the slope of the line. Vollenweider (1960) indicated that instead of one line as suggested by Rodhe's graphs there are a family of lines having the same slope, differing only in the intercept z_i. He indicates that the relationship between these two productivity parameters (π and P_{opt}) is determined by the optical properties of the water. Fee (1973), whose values for integral productivity in Lake Michigan would classify it as eutrophic, suggested that the ratio π/P_{opt}, which is really z_i, may be a more sensitive indicator of trophic state than integral photosynthesis.

Figure 4 is a graph of the relationship between z_i and trophic state. A P_{opt} of 50 is assumed. The extinction of light by non-chlorophyll material is represented as a constant ($k_w = .03$, 0.3, and 3.0) and as a variable dependent on chlorophyll concentration. The graph indicates that z_i would only be a sensitive index of trophic state if k_w does change as a function of chlorophyll. The z_i calculated with the variable k_w does decrease significantly as trophic state increases suggesting that it could be a sensitive indicator of trophic state.

Megard, et al. (unpublished) has suggested that the ratio of measured integral productivity to maximal potential productivity (the productivity obtained as k_w approaches zero (Bannister 1974), could be used as an alternative to other trophic indices. Relative integral photosynthesis (π_{rel} or π/π_{max}) is a measurement of how photosynthetically active radiation (PHAR) "is partitioned between the phytoplankton and the environment." From equation 28 of Bannister (1974) it can be shown that

$$\pi \text{ rel} = \frac{\pi}{\pi \text{ max}} = \frac{k_w Chl}{k_w Chl + k_w}$$

and that π_{rel} is the fraction of PhAR that is absorbed by chlorophyll. Megard et al. (unpublished suggests that the ranges of π_{rel} can be associated as follows with the traditional trophic types: oligotrophic ($\pi_{rel} < 0.1$), eutrophic ($\pi_{rel} = 0.1$-0.5), and polytrophic ($\pi_{rel} > 0.5$).

A major objection to all these indices presented is that, except for the use of P_{opt} (Rodhe, 1958) they do not have the dimension of time; they have ceased to measure productivity. As such they have lost the essence of the reasoning behind measuring productivity; that is, that it is a measurement that gives insight into the dynamics of the aquatic system. If integral productivity is insensitive to trophic change, then it seems appropriate to modify the dynamic measurement rather than to abandon it for a static one. The use of P_{opt} as a dynamic index would seem to be appropriate, but its relationship to integral productivity is affected by light absorption in the water column and by itself it appears to have little meaning in the understanding of the dynamics of the lake. Indeed, the dynamic component of P_{opt} is the productivity per unit chlorophyll (P_{max}) which is not thought to vary as a function of trophic state. The other component of P_{opt} which does vary with trophic state is chlorophyll concentration, a static variable.

Horne et al. (1975) critized the whole assumption that primary productivity is best measured on an areal basis. The original intent of the use of the primary productivity as the trophic criterion was that the measurement would imply the condition of the total lake biology (Naumann, 1927). In the argument of Horne et al. (1975) areal primary productivity would not accomplish this because zooplankton feed on a volumetric rather than an area basis. If, as has been applied, in this paper, similar primary productivity values are possible in lakes different of widely different concentrations of algal biomass, then similarly low correlations should be found between areal productivity and secondary production, which is also a function of biomass concentration.

A possible alternative to areal primary productivity was suggested by Palalas (1975). He found that integral productivity is also misleading in shallow lakes where the total possible integral productivity was never reached because the euphotic zone is greater than the depth of the lake. He suggested that productivity should be based on the amount of carbon fixed per unit volume of the lake. This can be calculated by weighing the rates of carbon assimilation at each depth by the volume of the same strata and dividing their sum by the total lake volume. In very large lakes he suggested that the division of the integral productivity by the mean depth would be acceptable.

Expression of productivity in terms of lake volume eliminates the problems found using integral productivity both in shallow lakes and in those with low k_w, and therefore, with potentially deep euphotic zones. In addition, expressing productivity on a volumetric basis allows it to be used directly in models of secondary productivity. It might be expected that estimates of secondary productivity will relate better to this volumetric measurement than to the areal representation.

MULTI-VARIABLE INDICES

Single variable indices have been criticized for lack of sensitivity to the total complexity of the concept of trophic state (Brezonik and Shannon, 1971). The concept is said to be hybrid, incorporating aspects of both nutrient status and productivity. Therefore, in order to reflect the totality of the concept, many or all of the criteria used to differentiate trophic state must be incorporated into the index.

Many of the multi-variable trophic indices have been reviewed by Shapiro (1975). In this report three indices will be reviewed, each differing fundamentally in its construction. Several points about the construction of the indices will be raised:

1. Do the indices accomodate lakes outside their original data base?
2. If correlated parameters are used, does the index recognize the correlation? If the relationships among the parameters is non-linear, does the index compensate for this?
3. Do the multi-variable indices indeed reflect a greater part of the trophic concept than do single indices?
4. As the addition of more variables costs money, does the increase in accuracy justify the expense?

The Michalski-Conroy Index

The first multi-variable index to be discussed was constructed by Michalski and Conroy (1972). The index is numerical, ranking lakes between values of zero to ten. Zero represents the "worst" value found in the lakes examined, and ten represents the "best." Intervening values are calculated using the equation

$$\text{Rank} = \frac{10\ (x-y)}{z-y} \quad \text{where}$$

x is the value for a given lake

y is the minimum value for all lakes in the data set

z is the maximum value for all lakes in the data set

The result is a ranking index which linearly divides the trophic spectrum between the highest and lowest values for each parameter used. The separate variable indices are then averaged to obtain a single index value for the lake.

The index includes mean depth, a morphometric variable which is considered to be of importance in determining lake productivity (Rawson, 1955; Vollenweider, 1968, 1976). Secchi disk transparency and chlorophyll are used to indicate the amount of algal biomass. The morpho-edaphic index (Ryder, 1965) has been used to predict fish productivity. The shape of the oxygen curve and the Fe:P ratio in the bottom waters are used to indicate hypolimnetic changes. No index of macrophytes is included.

Because the ranking system depends on the range of values found in the present data base, additions of lakes with values outside the present maximum and minimum values requires that every lake in the data set would have to be reclassified. In the index presented in 1972 the chlorophyll values range from 1.1 to 18.3 mg/m^3 and transparency from 1.6 to 8.1 meters. Although this limited range of values reflects admirably in the status of lakes in Ontario, the range would have to be expanded considerably before it could be used worldwide.

A more serious criticism of the index in its present form is that there is no consideration of correlated variables. It is either assumed that none of the variables are correlates (i.e., that they all change independently of the others) or that correlated variables are related linearly so that a given degree of change in one will correspond to the same degree of change in the other. Chlorophyll and Secchi disk transparency are known to be correlated variables, but the relationship between them is not linear. As the index does assume linearity, the result is a hyperbolic relationship between the index ranks (Figure 5). The discrepancies that develop with this treatment of the data are not the result of any real differences within the lake between the degree of transparency and the amount of chlorophyll but only the result of how the index handles non-linearly correlated variables.

The correlation of the Michalski--Conroy index values with the Carlson index values are listed in Table 4. The correlation coefficients are high. Slightly higher correlation coefficients are obtained if the two Carlson index values are averaged. The regression line relating the Chlorophyll TSI with the Michalski-Conroy index (Fig. 6) shows the effect of the limited data base. The scale has an effective range only from TSI's of 29 to 67. Many lakes are excluded on both ends of the scale.

The Environmental Protection Agency Index

The Environmental Protection Agency (1974) devised a lake classification index to use in conjunction with their National Eutrophication survey. Like the index by Michalski and Conroy (1972), this index is also relative, with the extremes of the index being dependent on the original data base (in this case, 200 lakes).

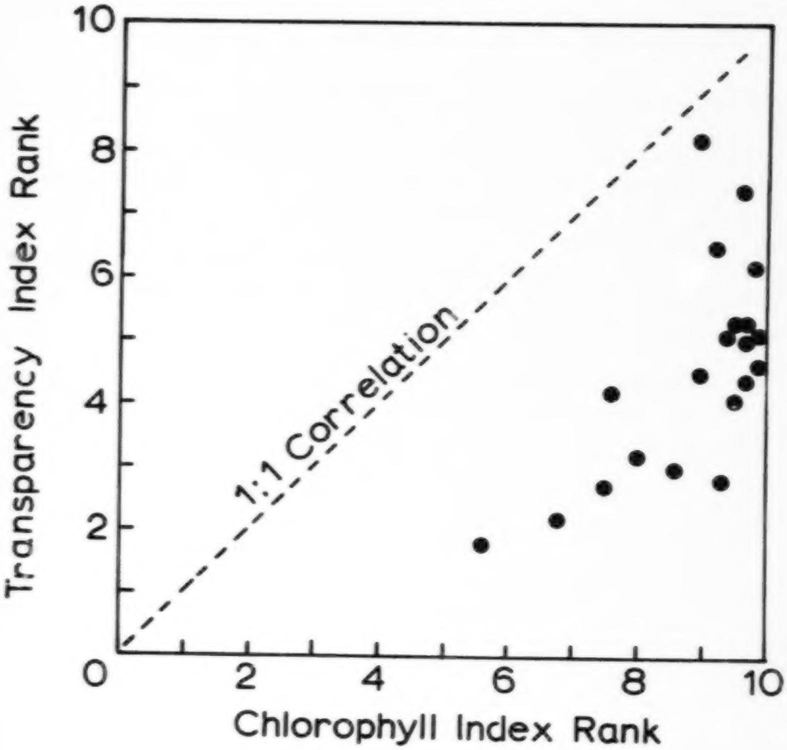


Figure 5. The relationship of the Michalski-Conroy index values for chlorophyll and Secchi disk transparency.

Table 4. A comparison of the Michalski-Conroy index with the trophic state index of Carlson (1977).

Carlson Index Variable	Correlation Coefficient	Regression Equation
Chlorophyll	0.86	$\ln Y = 4.05 - 0.060 \, (TSI)$
Transparency	0.83	$\ln Y = 4.80 - 0.082 \, (TSI)$
Average Index	0.89	$\ln Y = 4.64 - 0.076 \, (TSI)$

Y = Michalski-Conroy index

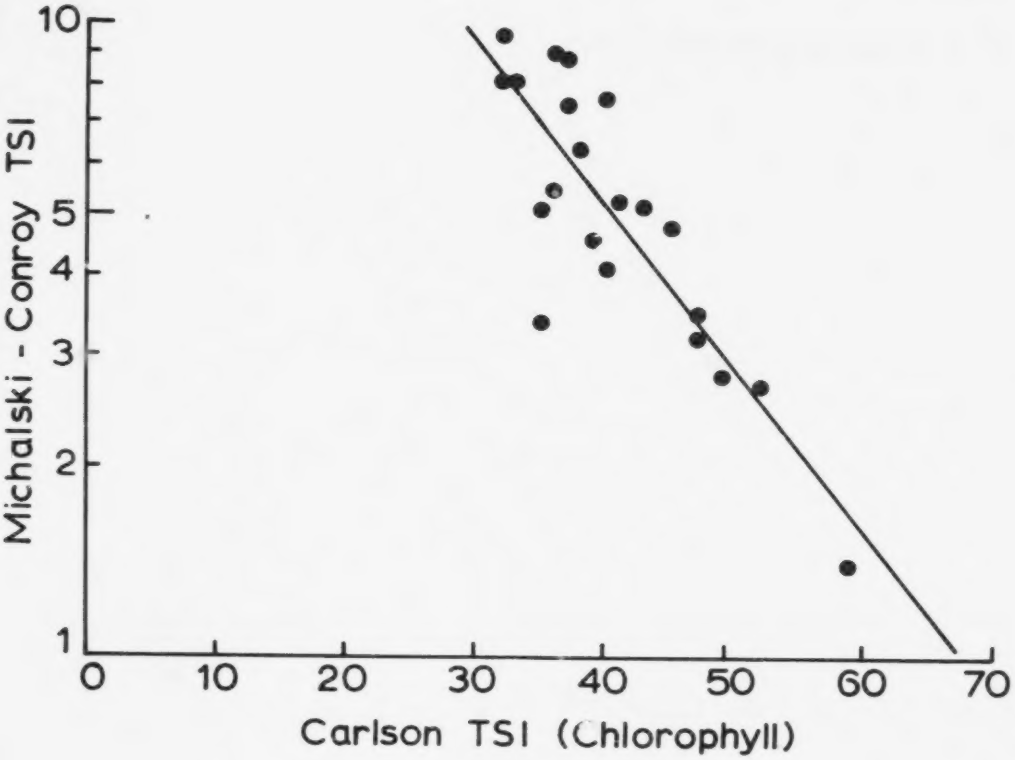


Figure 6. The relationship between the trophic state indices of Michalski-Conroy and Carlson. The Carlson index values was derived from the chlorophyll data.

The index uses six variables. Three of these (total phosphorus, dissolved phosphorus, and inorganic nitrogen) are open-water nutrient variables, two (Secchi disk transparency and chlorophyll) are open-water biological variables, and one describes the oxygen concentration in the hypolimnion.

Instead of a linear division of the intervening values between the maximum and minimum values for each variable, the index calculates the percentage of the lakes that have higher values than the value found in a given lake. Values for each variable can have an index value of 0 to 100. These index values are simply summed, resulting in the final index having a range of 0 to 600. If data are obtained that exceed the maximum or minimum values used in the index, they are simply assigned values of 600 or 0 under the premise that "the index would not be sensitive enough to show changes anyway."

The unique method described above for obtaining the initial index values results in a non-linear relationship between the variable and index values. This non-linearity is illustrated for total phosphorus, chlorophyll, and Secchi disk transparency in Figure 7. This non-linearity apparently provides a correlated relationship between the index values, but the relationship is not necessarily the same as that obtained by others for the same variable. In Figure 8 the relationships between chlorophyll and Secchi disk transparency and between chlorophyll and total phosphorus are graphed using the values corresponding to EPA index values of 5, 10, 15 etc. for each variable. In both instances a close log-log relationship is obtained between the variables. However, when compared to the relationships obtained by Carlson (1977) for these same variable, it is seen that the relationships relating to total phosphorus are entirely different. A possible reason for this is that some of the total phosphorus values are extremely high (1,525 mg/m^3) and may actually be not well correlated with other variables. In Figure 9 the values of chlorophyll and total phosphorus are plotted and compared with the regression lines of Carlson (1977) and Dillon and Rigler (1974). The closeness of fit for most of the points to the line suggest that the procedure of autocorrelating variables used in the EPA index was not really necessary. The index could have been derived using simpler regression techniques.

The results of the correlation of the Carlson single variable index with the multi-variable EPA index (Table 5) indicate that all of the three variables correlate well with the index. The regression lines for chlorophyll and Secchi disk transparency with the EPA index are nearly identical, while the total phosphorus line is very different.

The relationships between the EPA index and the Carlson indices of chlorophyll and total phosphorus are shown in Figure 10. The regression line for the Secchi disk transparency index is also superimposed on the chlorophyll index graph. This striking dissimilarity of the total phosphorus index line from the other is

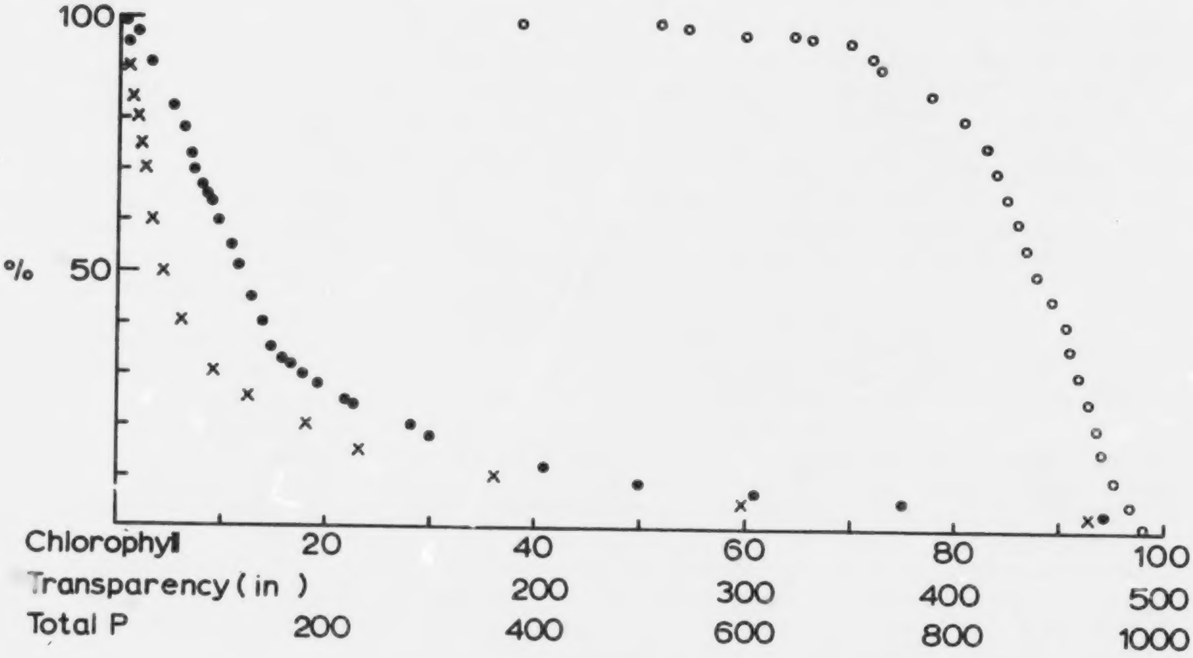


Figure 7. An illustration of the non-linearity in the relationship between the EPA index values (as represented as % of maximum value) and the values for Secchi disk transparency (o), chlorophyll (●), and total phosphorus (x).

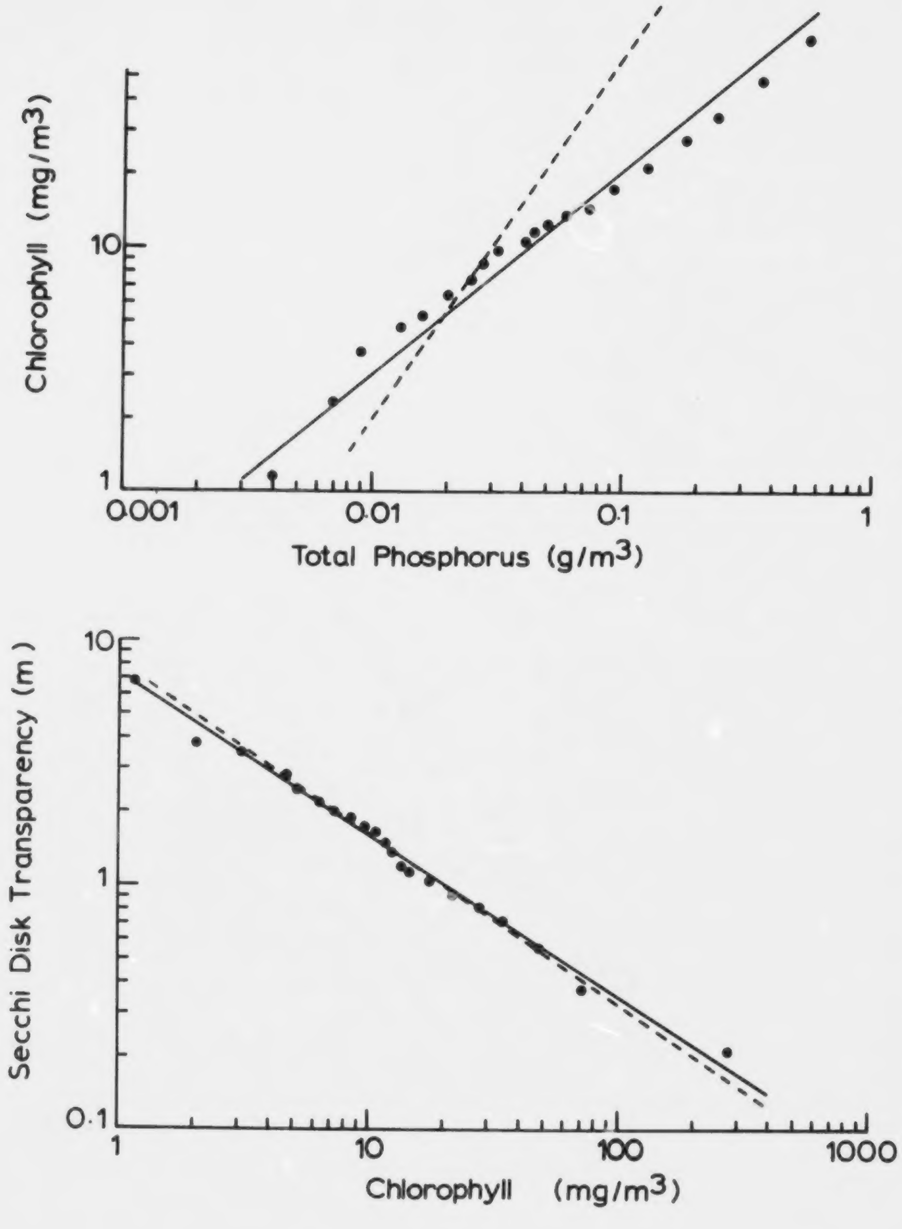


Figure 8. An illustration of the internal correlation of parameters in the EPA index. The dashed line represents the regression line obtained between these parameters by Carlson (1977).

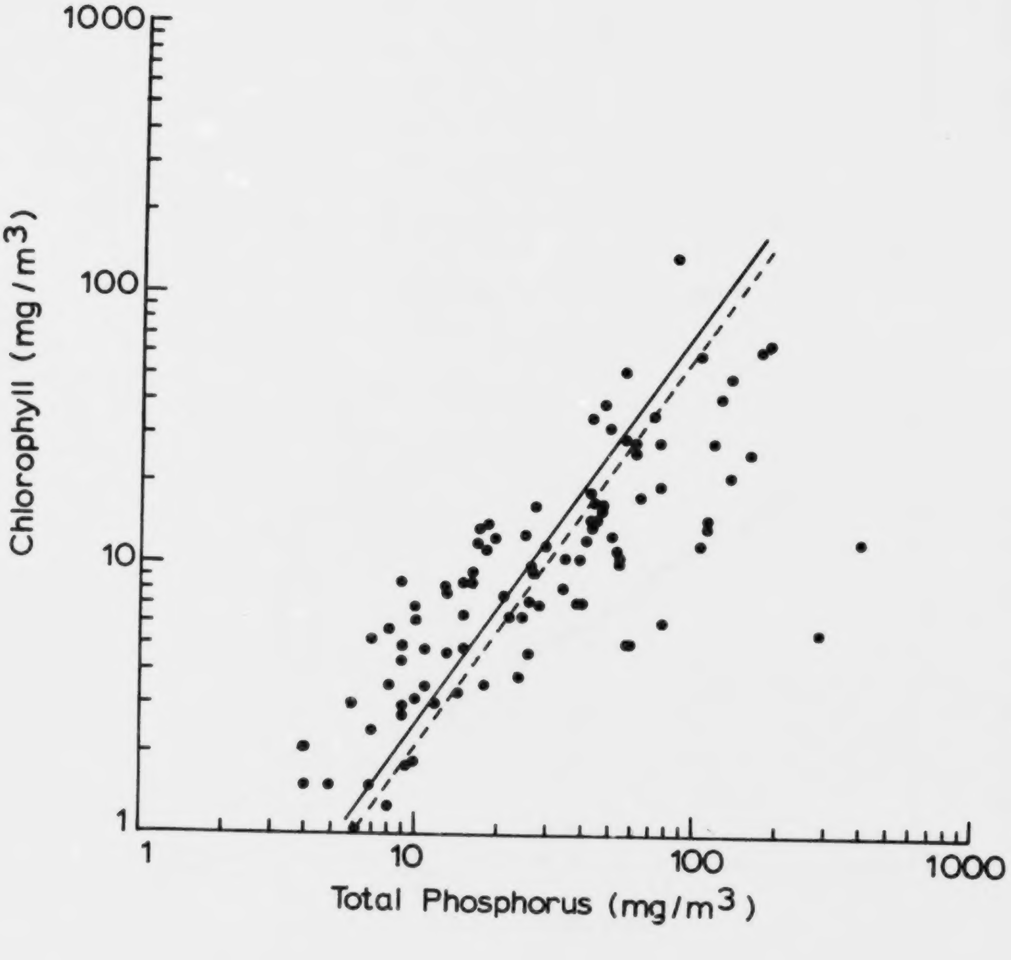


Figure 9. The relationship between total phosphorus and chlorophyll obtained using the EPA data. The lines represent the regression lines obtained between these parameters by Carlson (solid line) and Dillon and Rigler (dashed line).

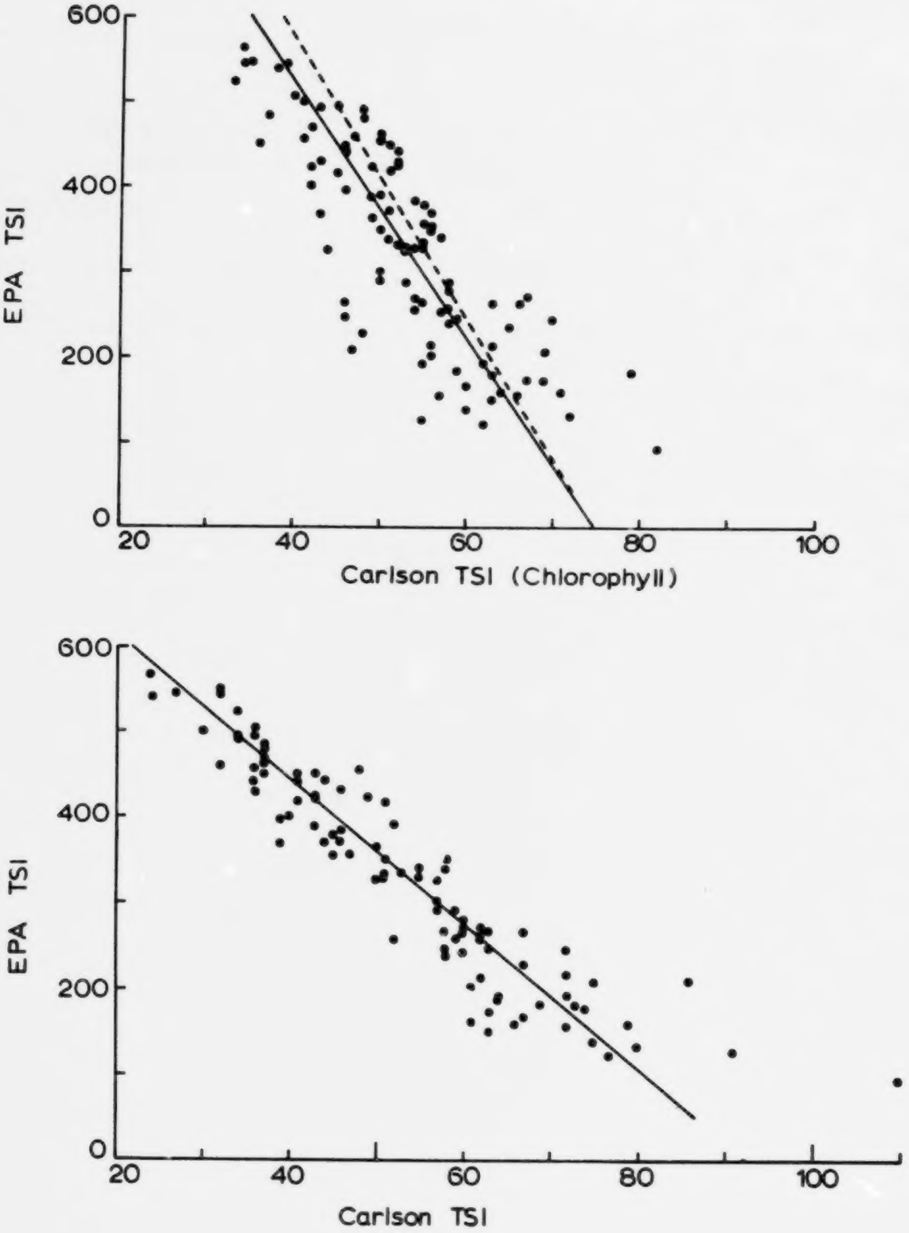


Figure 10. The relationship between the EPA trophic state index and the Carlson index. Upper graph: the Carlson index values are derived from chlorophyll data. The dashed line represents the Secchi disk regression line. Lower graph: the Carlson index values are derived from phosphorus data.

Table 5 . A comparison of the Environmental Protection Agency index with the trophic state index of Carlson (1977).

Carlson Index Variable	Correlation Coefficient	Regression Equation
Chlorophyll	0.82	Y = 1139 - 15.26 (TSI)
Transparency	0.81	Y = 1166 - 15.58 (TSI)
Total Phosphorus	0.93	Y = 783 - 8.47 (TSI)

Y = EPA index

readily seen. The limitations of the EPA index in relation to the possible range of values actually found is also apparent. The chlorophyll and transparency regressions suggest its range is from about 35 to 75 Carlson TSI units, while the phosphorus index suggests a broader scale from 22 to 102 units. The total index may have a range somewhere less than indicated by the total phosphorus variable alone.

The Shannon and Brezonik Index

The index of Brezonik and Shannon (1971) differs markedly from the other two indices discussed in that it uses principal component analysis for the original formulation of the index. Seven indicators used in the formulation of the index are reduced to a single value by this technique. The first principal component is the linear combination of the variables which explains the maximum variance in the original data (Shannon and Brezonik, 1972).

Of the seven indicators used in the index, one is related to open-water nutrients (total phosphorus), three are open-water biomass variables (Secchi disk transparency, chlorophyll a and total organic nitrogen), two are related to the total ionic content of the water (specific conductivity and Pearsall's (1922) cation ratio) and one dynamic biological parameter (primary productivity).

The trophic state index values for a given lake are obtained from the equation:

$$\begin{aligned} \mathrm{TSI} &= 0.94\,(\mathrm{PriProd}) + 0.92\,(1/\mathrm{SD}) + 0.90\,(\mathrm{TON}) + 0.86\,(\mathrm{CHA}) \\ &\quad + 0.80\,(\mathrm{COND}) + 0.74\,(\mathrm{TP}) + 0.63\,(1/\mathrm{Cat\ Ratio}) + 5.19 \end{aligned}$$

where the symbols in parentheses represent standardized values for each parameter. Standardization is accomplished by means of the equation:

$$z_{ij} = (x_{ij} - \bar{X}j)/\sigma j$$

Where:

x_{ij} = i^{th} value for variable j

$\bar{X}j$ = the mean of variable j

σj = the standard deviation of variable j
(Brezonik, 1976)

The values for Secchi disk transparency are corrected for color using the equation:

$$1/\mathrm{SD} = 0.15\,(\mathrm{Turbidity}) + 0.003\ \mathrm{Color}$$

The values for the lakes are scaled to a color of 75 platinum units (Brezonik, 1976). Because of this correction, actually twelve variables rather than ten must be measured in order to obtain an index value.

The Shannon-Brezonik index correlated well with all three of the indices in the Carlson index (Table 6) although the total phosphorus index produced a different slope than did the Secchi disk transparency and the chlorophyll indices (Fig. 11). The average index value of the Carlson index slightly improved the correlation with the index.

The Shannon-Brezonik index in its present form is considered preliminary. It is a relative index with the index values based on the original data set used in the first principal component extraction. As the original data set is from a limited geographical area (Brezonik, 1976), there may be peculiarities in the data that may require that the index be first based on a larger data set.

A major limitation of the Shannon-Brezonik index is the large number of variables that must be measured in order to produce an index value. In its present construction, all twelve parameters must be measured to obtain an index value. Brezonik (1976) acknowledges this fact and suggests that conductivity and the cation ratio could be eliminated without much loss in discrimination. He also suggests that the measure of primary productivity is a "complicated and time-consuming procedure" as well as being correlated with other measurements incorporated in the index. He suggests that it also could be eliminated. With these eliminations, the index would be constructed using transparency, chlorophyll, total phosphorus, and total organic nitrogen. As three variables have already been shown to be correlated (Carlson, 1977), and total organic nitrogen is probably also correlated, the ability of this multivariate index with its present choice of variables to be more useful than an index using only one of these variables is questionable.

A comparison of the indices.

Although these three multi-variable indices do not exhaust the types of indices now used, they represent three of the most popular of the indices, and they serve as examples of how multivariable indices can be constructed. Let us now consider these indices in relation to the four questions posed in the beginning of the chapter.

1. Do the indices accomodate lakes outside their original data bases? Only the Shannon-Brezonik index does this. Both EPA and Michalski-Conroy indices are limited by the data bases. In both of these indices the incorporation of lakes outside the original data bases requires a reclassification of every lake or the arbitrary assignment of the highest or lowest index value to

Table 6. A comparison of the Shannon-Brezonik index with the trophic state index of Carlson (1977).

Carlson Index Variable	Correlation Coefficient	Regression Equation
Total Phosphorus	0.88	$\ln Y = 0.04\ (TSI) - 0.96$
Chlorophyll	0.86	$\ln Y = 0.06\ (TSI) - 1.61$
Transparency (Uncorrected for color)	0.84	$\ln Y = 0.06\ (TSI) - 1.92$
Average Index	0.94	$\ln Y = 0.06\ (TSI) - 2.04$

Y = Shannon-Brezonik index

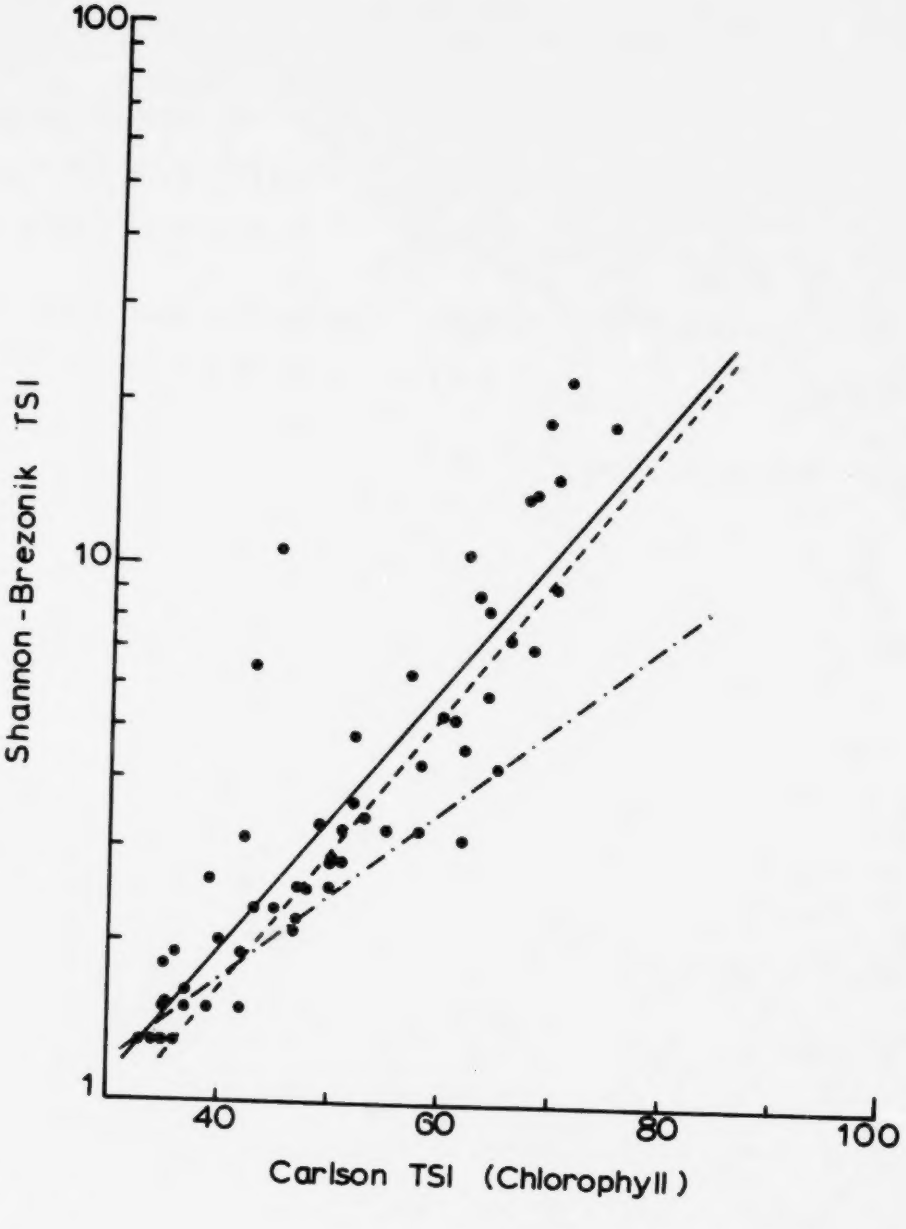


Figure 11. The relationship between the Shannon-Brezonik index and the Carlson index. The data points and the solid curve is derived from chlorophyll data. The other curves illustrate the regression lines obtained from Secchi disk transparency (---) and total phosphorus (-.-.) data.

the lake. These indices are limited to their original data bases because their scales are constructed using the highest and lowest values found in the original data base as the maximum and minimum index values. The Shannon-Brezonik index uses instead a mean value for each index variable as the basis for the scale, and the scale is open-ended. The Carlson index is open-ended only on the eutrophic end, but the value of zero chosen for the oligotrophic side exceeded all known values so that there would be no chance that the values for a particular lake could ever exceed the lower end of the scale.

The Michalski-Conroy and the EPA indices could be constructed to include all possible values simply by expanding the scales to include a larger range of variable values, but the problem with this maneuver is that the median values for most trophic variables in natural bodies of water are clustered near one end or the other of the total range of possible values. For instance, total phosphorus values might range as high as 20 or 30 mg/l, yet oligotrophy and eutrophy are determined at values of 10 to 20 ug/l. A linear scale including the total range of values would leave little sensitivity in the range where the changes of interest take place. The Carlson index overcomes this problem by using the logarithm to the base two, which tends to normalize the data (Shapiro, et al., 1975). A logarithmic transformation of the Shannon-Brezonik index also resulted in near-normal distribution (Van Belle and Meeter, 1975 as cited in Brezonik, 1976).

2. Does the index use correlated variables, and if so, are the relationships correctly represented? Correlated variables are redundant, providing no extra information about the lake and tend to weight the index. All the indices considered incorporate at least some correlated variables. Transparency and chlorophyll are found as variables in all the indices, yet both measure algal biomass. The Shannon-Brezonik index also includes organic N which should be strongly related to algal biomass. Table 7 compares the variables used in the indices. For the most part, however, the indices avoid known correlated variables, attempting instead to capture the broadest expression of trophic state using the fewest number of measurements.

The indices vary in their ability to handle non-linear relationships among variables. Using its unique ranking system, the EPA index essentially derives a relationship between all the variables, although the relationships are not necessarily the same as found by other people. The Michalski-Conroy index assumes no relationships among the variables, which causes difficulties where non-linear relationships actually exist. The Shannon-Brezonik index assumes a linear relationship among all the variables except for transparency which is a reciprocal relationship (1/SD). Both the Michalski-Conroy and Shannon-Brezonik indices could be easily modified to accomodate non-linear relationships. The EPA index appears to be unmodifiable without fundamentally changing its structure.

Table 7. A comparison of the trophic components incorporated in three multi-variable indices.

Trophic Component	Michalski-Conroy Index	Shannon-Brezonik Index	EPA Index
Open Water Biomass	transparency chlorophyll	transparency chlorophyll organic N	transparency chlorophyll
Open Water Nutrients		total P	total P inorganic N dissolved P
Hypolimnetic	Fe: P shape of O_2 curve		minimum O_2
Productivity		primary productivity	
Total Ionic Content	morpho-edaphic index	Pearsall ratio conductivity	
Morphometric	mean depth		

3. Do multi-variable indices reflect a greater part of the trophic concept than do single variable indices? All of the indices attempt to broaden the scope of classification to include several facets of the trophic state concept. Open-water algal biomass and open-water nutrient concentrations are most heavily emphasized (Table 7). Only the Shannon-Brezonik index utilizes a measurement of primary productivity, a popular criterion of trophic state. The Michalski-Conroy and the EPA indices consider hypolimnetic oxygen concentrations. None of the indices consider macrophytes which may compose the larger fraction of plant biomass in smaller lakes.

4. Is their increase in the number of variables justified? This question is difficult to answer. The correlations with the single-variable Carlson index are all high. Averaging the three Carlson variables (essentially making it a multi-variable index) only slightly increases the correlations. It could be argued that these high correlations suggest that single-variable indices are just as efficient at classification as the multi-variable indices. On the other hand, it might be argued that as the correlations were not perfect, the variance in the correlations is not just random scatter but real differences in trophic status that the multi-variable indices were able to detect that went unnoticed by the single-variable index. This argument can be effective as there is no trophic standard against which all the indices can be compared. There is no way to determine which argument is correct.

From a practical standpoint, my opinion is that the multi-variable indices have failed to justify the added expense, time, and additional expertise necessary to produce them. The indices are simply harder to use. The Michalski-Conroy index is the most preferable of the indices in that the index can be obtained from any number of variables, and therefore, it can be adapted to the facilities and resources of any given user.

In the Shannon-Brezonik and the EPA index, values for all the variables must be gathered before an index value can be obtained. If a single analysis of a variable is lost, as does sometimes happen, the lake could not be classified without a second visit and a complete reanalysis.

In an earlier chapter I compared various suggestions of the limits of oligotrophy and eutrophy to the Carlson index. The results of that comparison suggested that a TSI value of 40 was the upper range for oligotrophy and a value of 50 was the lower range for eutrophy. The authors of the three multi-variable indices have also suggested trophic limits for their indices. I have transformed their values into Carlson index values in Table 8. Both the Michalski-Conroy and the EPA index indicate limits that are close to those obtained in the earlier comparison. The Shannon-Bresonik index tends to place a better water quality designation on a given index value than would the other indices.

Table 8. A comparison of the trophic state designations of the multi-variable indices.

Index	Index Value	Corresponding Carlson Index Value
Michalski-Conroy Index Trophic Designation		
Excellent Water Quality	> 6	< 38
Vulnerable Water Quality	3-6	38-49
Poor Water Quality	< 3	> 49
EPA Index		
Oligotrophic	> 500	< 42
Mesotrophic	420-499	42-47
Eutrophic	< 420	> 47
Brezonik Index		
Ultra-Oligotrophic	1.3-1.9	31-38
Oligotrophic	2.0-2.9	39-45
Mesotrophic	3.0-6.9	45-59
Eutrophic	7.0-9.9	59-65
Hypereutrophy	> 10	> 65

This paper has discussed only several of the many types of lake indices that are presently available. This diversity of indices underscores the confusion that exists today as to the best way to define and describe the concept of trophic state. These concluding remarks will attempt to set this discussion of various indices into a larger perspective in order to suggest a common basis for the understanding of the trophic concept.

By 1927, Naumann had largely formulated the trophic concept. In a paper published in that year, many of the basic statements incorporated in the present concept were presented. Four of the most important of these statements are presented below.

1. The productivity of waters is determined by several factors but primarily by the concentration of nitrogen and phosphorus.

2. There are regional variations in productivity which correlate with the geological structure of the watershed.

3. The amount of nutrients affects not only the phytoplankton but also the lake biology as a whole.

4. There are certain evolutionary connections between lakes of the various types.

In these four statements is embodied the essence of the trophic concept. These statements suggest not a confused or even controversial issue, but rather a clearly stated conceptual model of how a lake ecosystem might respond to inputs of nutrients or other forcing factors. The trophic concept incorporates two basic aspects of a systems approach: the stimulus or forcing factor and the system response (changes in lake biological dynamics and structure). It has been argued by others that the term "trophic state" should be applied solely to the measurement of the stimulus (the rate of nutrient supply). On the other hand, it could also be applied to the system response. The emphasis on response rather than stimulus allows for the possibility that factors other than nutrient supply may also effect a system response.

If trophic state determinations are based on the system response, then the major problem faced in the construction of an index is the selection of the variable or variable that adequately reflect the total lake biotic system. Multi-variable indices appear to be best suited for this purpose as they can incorporate several disparate aspects of the system, therefore reflecting a larger fraction of the system's response.

The problem with multi-variate approaches is in the method of combining the measurements of the various system components. The methods reviewed in this paper all result in a loss of information, and this loss is critical. As the relationships among the system components are assumed to be unknown or to not exist in these combinations, the indices forfeit the ability to discriminate the individual status of any given component. They must assume that trophic state is the average response of the system, even though wide disparities in response may occur in the separate system components. The ability to use the index to predict future trophic states is hampered because prediction assumes the knowledge of the relationships between system components. The net effect of the multi-variable index is to provide a comprehensive lake classification system which provides an average lake classification, not necessarily correlated well with any given system component and having little predictive capability.

The single-variable indices have the opposite problem. Because they are related to only a single-system component, the potential for predictability is large. However, the extension of the prediction to another system components is limited by the knowledge of the relationships among the components. If, however, the relationships were known, then the status of all the biotic components could be estimated. Besides the potential for predicting future trophic states, the index based on a single component or system aspect has the advantage of an ease of interpretation. Unlike the multi-variable index which produces an average value the single variable index is not an average of several non-related components and interpretation of the index value is more direct. The disadvantage of the single variable index is in the classification of the whole lake system. Although it may classify one component well, its ability to classify the entire lake system is dependent on how directly the system components are related. The extent to which this will be a problem has yet to be examined.

Other considerations besides predictability and comprehensiveness must be considered in indices. Hooper (1969), Shapiro (1975), and Brezonik (1976) have suggested various attributes of the perfect index. Of their suggestions I would emphasize three criteria:

1. An index should be simple in technology, collection of data, and interpretation.

2. It should be universally applicable and incorporate all possible lakes.

3. It should be scientifically valid.

The first criterion is of fundamental importance in an index's construction. Multi-variable indices could incorporate so many measurements that the ability to use the index would be limited to only the best-equipped laboratories and the largest budgets. Perhaps the simplest index would be the one that incorporates the fewest necessary components. The index must also be simple in interpretation. If its explanation is so complex that the lay public cannot understand it, then it is of little use in communication.

The index must be universal. Any lake or reservoir should be able to be classified. The indices discussed in this paper that rely on the original data base clearly cannot meet this criterion. It would also be desirable if rivers and streams could also be classified by the same system. Using variables unique to lakes limits the index to lakes.

The index must also be a means of communicating our scientific knowledge, thus its basis must be scientifically valid. This means not only that the index should incorporate known relationships correctly, but more importantly, the index should be able to grow and develop as our knowledge of aquatic systems develops. An index cannot be static, allowing no further development or change beyond the original chosen variables. An index should be a tool that stimulates scientific investigation, not having as its sole function the placing of a name or number on a lake.

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THE CURRENT STATUS OF LAKE TROPHIC INDICES

- A REVIEW -

Joseph Shapiro

Limnological Research Center
University of Minnesota
Minneapolis, Minnesota

INTRODUCTION

The amount of time and effort expended during the last few decades in attempts to classify water bodies can be appreciated only by one who attempts to review the subject. Unfortunately the overriding impression one gets is that of a limnological tower of Babel. Virtually every characteristic of a water body, be it stream, river, or lake has been used as a basis for a classification scheme of one sort or another, and virtually every scheme is unique.

It is safe to say that the reason for this outpouring of work lies in the failure of the traditional classification scheme that divides lakes into eutrophic, oligotrophic, and more recently mesotrophic, categories. These categories, whether used in their original sense of nutrient concentration and supply, or in their later more widely accepted sense as descriptions of the consequences of low and high nutrient supplies, are inadequate. They are inadequate for descriptive purposes other than in a very broad manner, and they are inadequate for communication. This inadequacy for communication exists not only among limnologists so that one limnologist's eutrophy is another limnologist's mesotrophy, but it exists also between limnologists and laymen. The very word "eutrophic" has come to have a negative connotation to the public, to large extent because it is without quantification. Thus we find ourselves, three quarters of a century after Forel, unable to communicate with each other or with those who depend upon our sciences. This situation cannot be allowed to continue. If we are to use our information to manage lakes, to estimate their recreational potential, to estimate their sensitivity to degradation, to manipulate and restore them, we must have quantitative indices to characterize them. We can continue for theoretical purposes to classify lakes in an attempt to discover or describe groupings in which they or certain of their characteristics fail, but unless we can develop quantitative indices our results will languish as philosophical exercises forever unavailable to the wider world.

This problem has been recognized by others. As Russell Train pointed out in 1972, when he was chairman of the United States Council on Environmental Quality, despite the limitations of such indices as those for gross national product, cost of living, unemployment etc., they are critical factors in both formulating and evaluating economic and national policy. He states his belief that we must develop similar sorts of indices for environmental quality if the level of environmental policy and planning is to be improved.

This is what Shapiro had in mind in 1969 when he suggested that what limnology needed was something analogous to the Richter scale used for earthquakes -- an objective numerical scale whose derivation might not be known to all but whose significance has come to be appreciated through use.

The purpose of this paper is to present those indices we have been able to find in the literature so that they may serve as a guide toward development of indices which will serve us as standards and as means of communication with others. The discussion will be limited to indices developed primarily for lakes although a number of indices applicable to streams and rivers appear in the bibliography. Furthermore most of the indices to be described deal with the open waters of lakes as the problem of adequately characterizing the extent and nature of macrophytes has not been resolved satisfactorily. (Lind and Cottam, 1969)

As noted above, the array of indices is wide and their uses diverse. They may be categorized in a variety of ways. Thus there are whole lake, water quality, and trophic state indices; there are indices for determining recreational potential, for management purposes or for scientific studies; indices may be descriptive or analytical; subjective or objective; simple or complex; relative or absolute; biological, physical, or chemical; etc.

Which is best? Clearly the answer depends on the proposed use. However, there are certain features that an ideal index should embody.

1. It should be easy to arrive at through use of unequivocal data.
2. It should be simple in form.
3. It should be narrow enough in scope to realistically serve its purpose.
4. It should be objective in that it must contain no value judgment.
5. It should be absolute rather than relative so that it can be used anywhere.
6. It should be scientifically valid i.e. it should not use nonlinear relationships in a linear manner.
7. It should be retranslatable in the sense that if the index is a number derived from certain data the data should be derivable from the number.
8. It should be understandable to the lay public and to officials dealing with policy matters.

To facilitate discussion of the various indices, they will be described under four headings:

1. National Water Quality Indices
2. Whole Lake Indices
3. Relative Trophic State Indices
4. Absolute Trophic State Indices

The divisions are not perfect but will help in evaluating the indices.

I. National Water Quality Indices

Such indices have been developed to deal with water use problems. Probably many exist but two will suffice as examples.

1. In 1969 the National Swedish Nature Conservancy Office published a report describing a means of dividing waters into classes for three purposes -- bathing, water supply, and fishing. For their "general pollutional effects" waters were classed as:

A1 unpolluted
A2 slightly polluted
A3 distinctly polluted
A4 heavily polluted.

Among the criteria used were temperature increase, taste and odor increase, BOD increase, and increase in total P. Thus "distinctly polluted" waters had, among other features, an increase of total phosphorus of 100%. In classifying the waters for bathing purposes they were categorized as, B1, desirable , to B4, nonpermissible. Among the factors used here are Secchi disk transparency so that B1 lakes have a transparency greater than 3 meters and B4 lakes have a transparency less than 1 meter.

2. In 1975 Inhaber proposed a water quality index for Canada -- or actually two indices. Both are numerical and nondimensional with zero being best, and both use the root mean square of the values of the parameters to give sensitivity to extreme values of the indices.

A. In this index constituents are rated relative to one another on the basis of their estimated importance in affecting water use for (1) drinking, (2) fish and aquatic life, (3) recreation. Weighting is done as follows: if 0.015 ppm is the minimum concentration "tolerable" the weight of an effluent sample would be 66.7, if it took 66.7 liters of the receiving water to dilute 1 ppm of the effluent to the tolerable 0.015 ppm.

B. This index deals with what is in the water.

1. Trace metal contaminants.
2. Suitability of rivers in terms of turbidity for drinking supplies and contact recreation.
3. Mercury contamination of fish landed commercially.

Both of these "indices" may be useful in formulating national policy to a certain extent but they fulfill few of the criteria suggested above. In fact there is in these "indices" more than a small measure of "standards".

II. Whole Lake Indices

1. Recreational Indices.

An example of a recreational index useful for the specific purpose of rating lakes for their recreational use is presented by one constructed by the Department of Natural Resources of the State of Wisconsin. In principle, eleven aspects of the lake divided into four categories are given one of three ratings. The total rating of a possible 72 is the recreational rating of the lake. An example of the format is given in Figure 1.

2. Indices of Potential and Actual Lake Conditions

A. Bortleson *et al*. (1974) divided 24 criteria into three groups.

1. seven parameters affecting potential enrichment from natural causes
2. four factors affecting potential enrichment from culturally-related causes
3. thirteen indicators of existing eutrophication and water quality.

For each lake each criterion is given a rank of 1-5 (1 is best). For each category the ranks are summed. Ranks for the three categories are not summed. Twenty-five other indicators are checked as plus or minus to provide supplementary information. An example of the ranking of existing water quality factors is given in Figure 2.

Fig. 1. Example of the application of the recreational rating system. The lake is Pewaukee Lake, Wisconsin. (From the Wisconsin DNR, 1970)

Space: Total area - 2,493 acres Total shore length - 13.71 mi.
Ratio of total area to total shore length: 0.284

Quality (18 points for each item)

Fish:		
X 9 High Production	__6 Medium production	__3 Low production
__9 No problems	X 6 Modest problems such as infrequent winterkill, small rough fish problems	__3 Frequent and overbearing problems such as winterkill, carp, excessive fertility
Swimming:		
X 6 Sand or gravel (75% or more)	__4 Sand or gravel (25 - 50%)	__2 Sand or gravel (<25%)
__6 Clean water	X 4 Moderately clean	__2 Turbid or darkly stained
__6 No algae or weed problems	__4 Moderate algae or weed problems	X 2 Frequent algae or weed problems
Boating:		
X 6 Adequate depths (75% of basin >5')	__4 Adequate depths (50-75% of basin > 5' deep)	__2 Adequate depths (50% of basin)
X 6 Adequate size for extended boating (>1,000 acres)	__4 Adequate size for some boating (200-1,000 acres)	__2 Limit of boating challenge and space (<200 acres)
__Good water quality	X 4 Some inhibiting factors such as weedy bays, algae blooms, etc.	__2 Overwhelming inhibiting factors such as weed beds throughout
Aesthetics:		
__6 Existence of 25% or more wild shore	X 4 Less than 25% wild shore	__2 No wild shore
X 6 Varied landscape	__4 Moderately varied landscape	__2 Unvaried landscape
__6 Few nuisances such as excessive algae, carp dumps, etc.	X 4 Moderate nuisance conditions	__2 High nuisance conditons

Total quality rating: 57 out of a possible 72

Fig. 2. Ratings assigned to eutrophication and water quality factors for Washington Lakes. 1 is best, 5 is poorest. (From Bortleson et al., 1974)

Indicators	Rating				
	1	2	3	4	5
Total phosphorus upper water (μg/l)	<5	5-10	11-20	21-30	>30
Total phosphorus, ratio of bottom to upper waters	<1.0	1.0-1.5	1.6-3.0	3.1-10	>10
Inorganic nitrogen, upper water (μg/l)	<100	100-200	201-300	301-650	>650
Inorganic nitrogen, ratio of bottom to upper waters	<1.0	1.0-1.5	1.6-3.0	3.1-10	>10
Organic nitrogen, upper water (μg/l)	<100	100-200	201-400	401-800	>800
Specific conductance (micromhos at 25°C)	<20	20-50	51-100	101-500	>500
Color (Pt-Co units)	0-10	11-20	21-40	41-60	>60
Secchi-disc (m)	>8.0	5.1-8.0	3.1-5.0	1.0-3.0	<1.0
Dissolved oxygen near bottom (mg/l)	>8.0	5.1-8.0	2.1-5.0	0.5-2.0	<0.5
Water temperature near bottom (°C)	<5.0	5.0-7.0	7.1-10.0	10.0-15.0	>15.0
Fecal-coliform bacteria (colonies per 100 ml; mean value)	<1	1-5	6-50	51-240	>240
Percentage of lake surface occupied by emergent rooted aquatic plants	<1	1-10	11-25	26-50	>50
Percentage of shoreline occupied by emergent rooted aquatic plants	<10	10-25	26-50	51-75	76-100

The system, although very detailed, has certain difficulties. Thus, it requires vast amounts of information and uses highly diverse parameters such as bottom temperature and fecal coliforms in the same grouping.

B. Bailey (1974) has proposed a three-dimensional lake classification scheme for lakes in the state of Maine. One axis would be "trophic status" as indicated by indicator organisms and other indirect measures. One axis would be "vulnerability to input" due to morphological or hydrological factors, and the third axis would be "intensity of cultural activity or impact". Trophic status would be indicated by the distance from the origin.

C. Uttormark (1974) has proposed a Lake Condition Index. Four parameters are given numerical ratings. The sum of all ratings is the index. Zero is satisfactory, 23 equals unsatisfactory.

The parameters and their values are:

Dissolved oxygen	0-6 points
Transparency	0-4 points
Fish kills	0-4 points
Use impairment	0-9 points
Possible total	23 points

The index does not relate well to specific nutrient loading (Fig. 3); also it is subjective. However, it is useful for management where alternative data are not available.

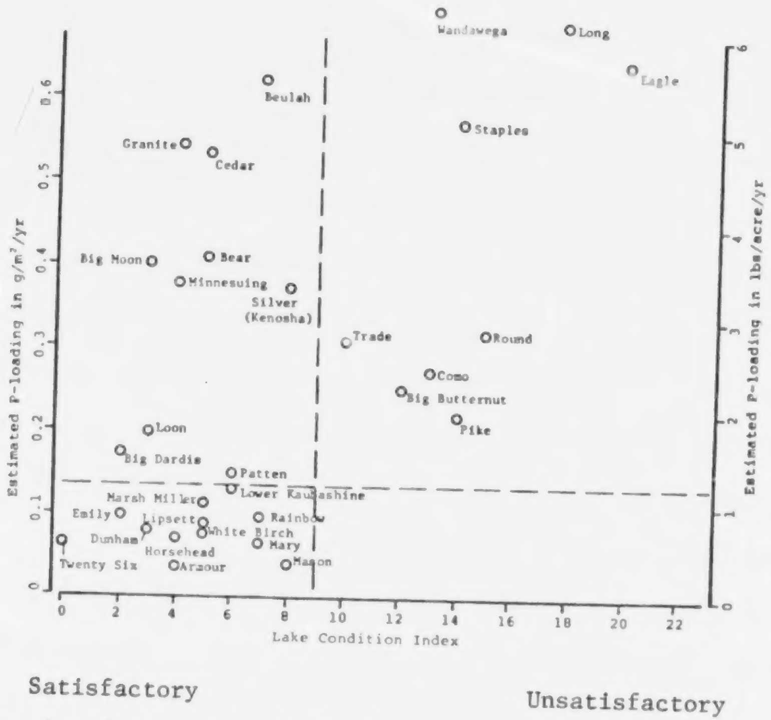

Fig. 3. Comparison of Lake Condition Index values and nutrient loadings for Wisconsin Lakes (from Uttormark and Wall, 1975).

III. Relative Trophic State Indices

All of the indices described here have the disadvantage that they are relative. That is, the position of any lake depends on the position of the other lakes in the array. This problem is less severe the more lakes there are involved but it does detract from the usefulness of the indices.

1. One of the simplest approaches was that of Lueschow *et al*. (1970) who ranked twelve Wisconsin lakes on the basis of the

mean annual values of five parameters significant to trophic status -- dissolved oxygen 1 meter above bottom; organic nitrogen; total inorganic nitrogen; Secchi disk transparency; and net plankton. The relative composite index is the sum of the individual ranks. An example is shown in Fig. 4.

2. A similar approach was used by Rawson (1960) in comparing twelve lakes in Saskatchewan, except that two rankings were made for each lake -- one based on five physical parameters and one based on three biological parameters. The scores are kept separate.

3. Reimers *et al*. (1955) used a proportionate ranking system to rank lakes on a scale of 10-0 where 10 was best and 0 worst.

Fig. 4. Composite rating of 12 Wisconsin lakes based on 5 parameters. (From Lueschow et al., 1970).

Crystal	8
Big Green	17
Geneva	17
Trout	19
Round	31
Pine	33
Middle	33
Oconomowoc	34
Mendota	45
Pewaukee	49
Delavan	52
Winnebago	52

They used several factors and determined the rankings as follows: For those parameters whose magnitude is directly proportional to productivity,

$$\text{rank} = \frac{10\ (\text{value} - \text{minimum value for all lakes})}{\text{range for all lakes}}$$

For those parameters inversely related to productivity,

$$\text{rank} = \frac{10\ (\text{maximum value for all lakes} - \text{value})}{\text{range for all lakes}}$$

4. A similar approach to that of Reimers *et al.* was used by Michalski and Conroy (1972) in Ontario, Canada. They used six parameters -- mean depth, Secchi disk transparency, chlorophyll *a*, Ryder's morpho-edaphic index, Fe/P in the hypolimnion, and dissolved oxygen in the hypolimnion. The final proportionate ranking, determined as in Reimers *et al.*, was the arithmetic average of all six ranks. Data used was for June to September. An example is shown in Fig. 5.

5. A system based on over 200 lakes was devised by the United States Environmental Protection Agency (1974). In this scheme the index is the sum of the percentile rankings for six parameters -- median total P, median inorganic N, median dissolved P, mean chlorophyll *a*, mean Secchi disk transparency, and minimum dissolved oxygen. Secchi disk transparency was used as

Fig. 5. Ranking of ten selected lakes in the Lake Alert Study area according to proportionate rankings of selected parameters. (From Michalski and Conroy, 1972).

Lake	PROPORTIONATE RATINGS						Average Rank
	Mean Depth	Secchi disk	Chlorophyll	Oxygen Distribution	Morpho-edaphic	Fe/P	
Gold	10.0	7.4	8.3	10.0	10.0	-	9.1
Anstruther	5.7	10.0	9.7	10.0	9.3	-	8.3
Mississagua	7.1	6.9	10.0	10.0	9.3	-	8.6
Catchacoma	7.9	5.6	10.0	10.0	9.6	-	8.6
Rathbun	4.4	6.9	7.8	3.3	10.0	-	6.4
Wolf Lake	1.1	0.4	7.3	10.0	0.0	-	3.7
Beaver Lake	2.0	5.2	6.4	0.0	5.8	1.8	3.5
North Rathbun	1.0	1.3	2.3	0.0	8.0	8.3	3.4
Loon Call	1.3	4.8	9.2	0.0	9.5	0.0	3.1
Cold	0.0	0.0	0.0	0.0	0.6	10.0	1.7

500-SD in inches, and dissolved oxygen was converted to 15-DO ppm to make them directly proportional to "trophic state". The index ranges from 0 which is worst to 594 which is best (Fig. 6). Lakes outside the range of the 200 on which the index is based are classed as either 0 if they are worse than any in the system, or 600 if they are better than any in the system.

In addition to the difficulty of these indices being relative, they have other problems as well. For example Michalski and Conroy can use only stratified lakes and certain of their categories are subjective. The EPA and Lueschow, both of whom sum their rankings, and Michalski and Conroy who average theirs, lose information and make it impossible to use the index to derive the data. All of the above indices lose information by being multivariate.

IV. Absolute Trophic State Indices

Such indices are arrived at independently for each lake.

1. Single Parameter

A. The areal hypolimnetic oxygen deficit of Hutchinson (1938) is an example of an index based on a single parameter. The infrequent use of this as an index may be due to its restriction to relatively large, deep, stratified lakes or to the fact that the system breaks down when the population of

Fig. 6. Percent of Maine lakes exceeding parameter value of each lake and the Trophic Index Number of each Maine lake using a data base of nine lakes. (From U.S. E.P.A., 1974).

Lake Code	Lake Name	Median Total P (mg/1)	Median Inorg N (mg/1)	500- Mean Sec (inches)	Mean Chlorophyll a (µg/1)	15- Min DO (mg/1)	Median Diss P (mg/1)	Index No. (Sum of Percentages)
2304	Estes Lake	0	0	0	11	0	0	11
2306	Long Lake	44	77	55	33	22	33	264
2308	Mattawamkeag Lake	22	44	22	55	11	22	176
2309	Moosehead Lake	77	22	77	88	66	66	396
2310	Rangeley Lake	55	55	66	44	55	55	330
2311	Sebago Lake	88	33	88	77	88	77	451
2312	Sebasticook Lake	11	55	11	0	33	11	121
2313	Long Lake	33	11	33	22	33	33	165
2314	Bay of Naples	66	88	44	66	77	77	418

algae is comprised primarily of blue greens. It does have the advantage of being easily and unequivocally determined.

B. Another single parameter proposed as an index is primary production. Rodhe (1958) suggested that all trophic lake types except oligotrophic and eutrophic be eliminated, and the rate of primary production be used as the measure of the degree of oligotrophy or eutrophy. While this approach has some merit it is difficult for administrators or laymen to relate to and thus may not be useful in dealing with the problem of communication.

C. An approach close to that of Rodhe has recently been suggested by Megard *et al.*(1975). They have suggested that the trophic index be that fraction of the photosynthetically active irradiance that is utilized by natural populations of algae. Two difficulties come to mind -- determination of the index depends on determining K_w, the attenuation of photosynthetically active light by the water, which is difficult to measure; and secondly, the index does not provide an intuitive feeling to non-limnologists.

2. Quotients

A. Various phytoplankton quotients such as that of Nygaard (1949) have been proposed. However as Brook (1965) points out they present difficulties. For example it requires a highly specialized knowledge of the phytoplankton to determine such a quotient and even then other investigators might not agree on the algal identifications. Furthermore they do not always work. Brook describes lake fertilizing experiments in which, even when the algal population was increased eight fold, the quotient did not change.

B. A similar yet different approach to the algal quotient index has been made by Stockner (1971). He proposed characterizing lakes on the basis of the ratio of Araphidinae/Centrales diatom frustules in the recent sediments. Basing his ideas on the differences in ratios between lakes of known characteristics, and on the changes in individual lakes resulting from fertilization, he proposed the following:

A/C ratio	Lake type
0-1.0	oligotrophic
1.0-2.0	mesotrophic
>2.0	eutrophic

Even assuming this system is valid, it requires expertise to determine the ratio and provides little intuitive feeling for the condition of the lake.

3. Indices based on lake fauna

A. Among those indices based on the fauna of lakes is that of Reynoldson (1958) who set up five categories ranging from extreme oligotrophy to eutrophy based on the characteristic species of triclad flatworms.

B. A similar approach was used by Jarnefelt (1953) who classified Finnish lakes on the bases of total bottom fauna, and Chironomid larve alone.

C. A numerical index based on Chironomid species was devised by Brinkhurst *et al.* (1960). The so called "trophic condition index", which ranges from 2.00 (extreme eutrophy) to 0 (extreme oligotrophy) is given by the formula:

$$\frac{\Sigma n_1 + 2\Sigma n_2}{\Sigma n_0 + \Sigma n_1 + \Sigma n_2}$$

Where Σ_0, Σ_1 and Σ_2 are the numbers of intolerant, moderately tolerant, and tolerant Chironomids per 100 dredge samples.

This index reflects reasonably well the conditions in the Great Lakes, western Lake Erie having an index of 2.00, Lake Ontario 1.07, and Georgian Bay, which is oligotrophic, 0.13. However, extension into other lakes is not likely to be useful as the relative abundance of the Chironomids is affected by their geographic range as well as by factors such as depth and water temperature having little influence on trophic status. In addition the range is small and Lake Erie which has an index of 2.00 is certainly not the most eutrophic lake in existence. Finally this index, as the two of Reynoldson and Jarnefelt, requires considerable expertise to determine and the results are not particularly intuitive to the layman.

In addition to phytoplankton quotients and indices based on bottom fauna, various investigators have developed indices using the fish in lakes.

D. For example in 1965 Ryder described his morpho-edaphic index, where $X = \frac{\text{TDS (ppm)}}{\text{mean depth (feet)}}$

From this rather hybrid index he claims to be able to predict fish production, Y, using the relation

$Y = 2\sqrt{X}$ where y is in lbs/acre/yr.

E. A somewhat more elaborate fish productivity index was published by Hayes in 1957 and modified by Hayes and Anthony in 1964. In its first form the PI (Productivity Index) is obtained by listing the recorded fish crop removed from each lake, summing up the weights of the species into groups with short, intermediate, and long food chains, and dividing the weights of each group by a factor given by Carlander (140, 43, and 16 respectively). The sum of the resulting three numbers is the Productivity Index.

This index which may be used to compare one lake with another may be converted to a Quality Index, QI, to enable lakes of different depths to be compared more reasonably.

Thus,

$$QI = PI\sqrt{m/5}$$

where m = mean depth in meters.

For example lakes Erie and Superior have Productivity Indices of 1.57 and 0.17 respectively, and Quality Indices of 2.92 and 0.90 respectively. In their later paper Hayes and Anthony modified the PI to take into account area, depth, and water chemistry as follows;

$$\log PI = -0.236 + 1.47 \times 10^{-4}x_1 - 0.517\ x_2 + 0.287\ x_3$$

where $x_1 = \sqrt{10^5/\text{area in km}^2}$

x_2 = log depth, m

x_3 = log methyl orange alkalinity, ppm

4. Multivariate Indices

Two approaches have been used in constructing absolute indices based on a number of parameters -- use of several factors simultaneously and use of several factors alternatively.

A. Perhaps the best example of the simultaneous use of multiple factors is in the work of Shannon and Brezonik (1972). Using annual averages of seven trophic state indicators in 55 lakes in the State of Florida they arrived at a Trophic State Index through the use of principle component analysis and other multivariate analytical methods. The parameters used were, primary production, chlorophyll a, total organic nitrogen, total phosphorus, Secchi disk transparency, specific conductance, and Pearsall's cation ratio $\left[\frac{Na + K}{Mg + Ca}\right]$.

The Trophic State Index or TSI was calculated as $TSI = Y_x + 5.19$

$$\text{where } Y_x = 0.919\frac{1}{SD} + 0.800\ COND + 0.896\ TON + 0.738\ TP + 0.942\ PP + 0.862\ CHA + 0.634\ \frac{1}{CR}$$

The validity of the index was demonstrated by the close relationship of the TSI values to the traditional trophic categories of lakes. Thus the group of lakes classed as hypereutrophic (Fig. 7) ranged in TSI from 10.5 to 22.1 while those in the ultraoligotrophic group had TSI values from 1.3 to 1.9.

While this index does have the advantage noted i.e. it seems to work -- it suffers from certain disadvantages. For example it is difficult to obtain all of the data, particularly as annual averages, and not all of the data are meaningful e.g. the cation ratio. Furthermore by using a combination of factors one loses information. Thus Lake Alice had a TSI of 10.7 putting it in the category of hypereutrophic, despite the fact that it had a moderate transparency and a low primary productivity and chlorophyll concentration. The lake does have a large population of water hyacinths however.

Fig. 7. Fifty-five Florida lakes ranked according to Trophic State Index (TSI). (From Shannon and Brezonik, 1972a)

Lake	TSI	Lake	TSI
Hypereutrophic group		Ten	3.2
Apopka	22.1	Palatka Pond	3.2
Twenty	18.5	Beville's Pond	3.1
Dora	18.5	Meta	3.1
Bivin's Arm	14.7		
Griffin	13.7		
Kanapaha	13.5	Oligotrophic group	
Alice	10.7	Jeggord	2.8
Eustis	10.5	Moss Lee	2.8
		Long Pond	2.8
		Clearwater	2.6
Eutrophic group		Altho	2.5
Hawthorne	9.1	Hickory Pond	2.5
Clear	8.6	Santa Fe	2.5
Burnt Pond	8.3	Sugga	2.3
Wauberg	7.4	Little Santa Fe	2.3
Newnan's	7.1	Adaho	2.2
		Wall	2.1
		Winnott	2.0
Mesotrophic group			
Twenty-five	6.4		
Harris	6.3	Ultraoligotrophic group	
Twenty-seven	5.8	Still Pond	1.9
Cooter Pond	5.3	Kingsley	1.9
Lochloosa	5.2	Geneva	1.8
Tuscawilla	4.8	Gallilee	1.6
Calf Pond	4.6	Swan	1.5
Orange	4.3	Anderson-Cue	1.5
Mize	4.2	McCloud	1.5
Watermelon Pond	3.6	Brooklyn	1.5
Little Orange	3.4	Cowpen	1.5
Weir	3.3	Long	1.3
Elizabeth	3.2	Sumter-Lowry	1.3
		Magnolia	1.3
		Santa Rosa	1.3

B. In the second approach to using multiple parameters to construct an absolute index the factors are used alternatively i.e. the index is obtained from any one of the factors and the other factors are used as corroboration. This has two advantages -- it is easier to gather the data, and because of the direct relationship between the data and the index the data can easily be translated from the index.

1. One such index has been proposed by Dobson (1974). Using data from near surface waters of lakes Ontario and Erie he found relationships between four "diagnostic variables"; 30/Secchi disk (m), chlorophyll a, total phosphorus, particulate organic carbon. Dobson proposed a scale of three aesthetic categories as follows:

Trophic Assessment

variable	low and good	medium and fair	high and poor
30/SD	0-4.9	5.0-9.9	10.0+
Chl a	0-4.3	4.4-8.7	8.8+
POC	0-270	280-550	560+
TP	0-8.6	8.7-17.3	17.4+

All of the variables are numerically related to the 30/Secchi disk as follows:

variable	factor
30/SD	---
Chl a	1.14
POC	0.179
TP	0.057

This system has certain disadvantages.

1. The terms "low", "good", etc. are subjective value judgments.
2. There are too few categories for precision.
3. The relationships used are not valid i.e. 30/SD is not linear and does not relate well to chlorophyll a.
4. The system was built on only two rather unusual lakes.
5. The system is unbalanced i.e. eutrophic is by far the largest category.

On the other hand this scheme has certain advantages or potential advantages.

1. Some of the data are easily arrived at.
2. Alternative parameters can be used.
3. There is an attempt to use defined relationships.
4. The scheme allows some determination of causal effects, e.g. one can tell, as the parameters are reported separately, whether a low transparency is due to chlorophyll or to turbidity.

2. A somewhat similar system with far fewer disadvantages has been proposed by Carlson (1974). Carlson's Trophic State Index, or TSI, is basically a linear transformation of Secchi disk transparency such that each major unit in his scale has half the transparency of the next lower unit. It is derived as follows:

$$TSI_{(SD)} = 10(6 - \log_2 SD)$$

where Secchi disk transparency is in meters.
Thus a lake with transparency of 64 m has a TSI of 0 which is at the low end of the scale. The other end of the scale is left open but probably does not extend much above 100 (Fig. 8).

By using empirically determined relationships between total phosphorus and transparency and between biomass, as represented by chlorophyll a and transparency, Carlson has made it possible to arrive at the same index value from these data as well. Thus,

$$TSI_{(TP)} = 10(6 - \log_2 65\frac{1}{TP})$$

and

$$TSI_{(CHL)} = 10(6 - \log_2 7.7\frac{1}{CHL^{0.68}})$$

where total P and chlorophyll a are in μg/l.

Fig. 8. Transparency, phosphorus and chlorophyll values corresponding to Carlson's Trophic State Index values. (From Carlson, 1974).

TSI	Secchi Disk (m)	Surface Phosphorus (mg/m^3)	Surface Chlorophyll (mg/m^3)
0	64	1	.04
10	32	2	.12
20	16	4	.34
30	8	8	.94
40	4	16	2.6
50	2	32	6.4
60	1	65	20
70	0.5	130	56
80	0.25	260	154
90	0.12	519	427
100	0.062	1032	1183

Calculation of the indices is facilitated by using the following equations:

$$TSI_{(SD)} = 10\left(6 - \frac{\ln SD}{\ln 2}\right)$$

$$TSI_{(TP)} = 10\left(6 - \frac{\ln \frac{65}{TP}}{\ln 2}\right)$$

$$TSI_{(CHL)} = 10\left(6 - \frac{2.04 - 0.68 \ln chl\ \underline{a}}{\ln 2}\right)$$

In similar fashion any parameter that can be correlated with transparency can be used to arrive at the same Trophic State Index values.

The advantages of this system are:

1. The index uses easily obtained data.
2. It is simple in form, being reported simply as a number.
3. It is narrow enough in scope to be meaningful i.e. it describes the "trophic" conditions in the open water and does not attempt to infer health, aesthetic, or other characteristics.
4. It is purely objective. No value judgments are used and no names are suggested for different ranges of TSI.
5. The TSI values are absolute and, having been derived from a wide variety of lakes, are applicable to many lakes.
6. The relationships used are valid i.e. transparency is not

treated as linear but cognizance is taken of the parabolic shape of the transparency/biomass relationship.

7. The index does not lose information by mixing up unrelated or even related parameters.
8. The data can be retrieved from the index.
9. The form of the index allows for an intuitive grasp of it in much the same fashion as the Richter earthquake scale does.
10. The index has sufficient categories for fine discrimination among lakes.

An example of the descriptive use of the index is given in figure 9 where the changes in Lake Washington over the period 1950 to 1973 are shown as both raw data and as TSI values. Although both show the same trends the TSI values are more sensitive indicators of change in certain instances. For example the change in chlorophyll concentrations from 1950 to 1960 does not appear to be great but it does represent a significant change in the value of the index. Another example of the descriptive use of the index is given in figure 10. Note that the TSI values of the Minnesota lakes almost fit a normal distribution. This is in contrast to a histogram constructed using equal intervals of Secchi disk transparency in which most values appear at the low end of the diagram.

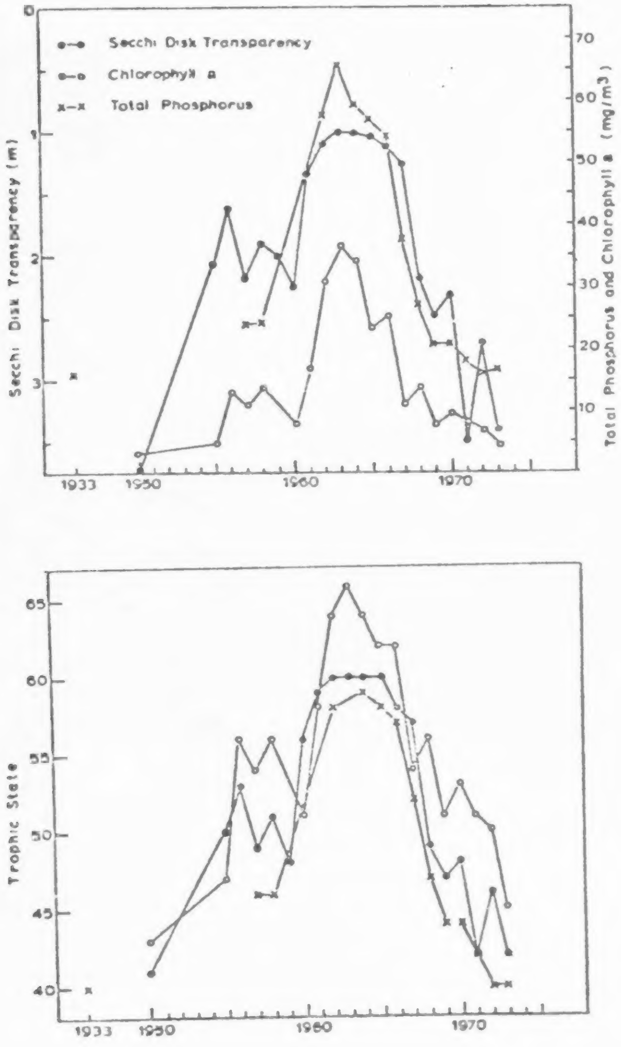

Figure 9. Top: Average summer values of three parameters in Lake Washington, Seattle, Washington. Below: The data transformed into Trophic State Index values.

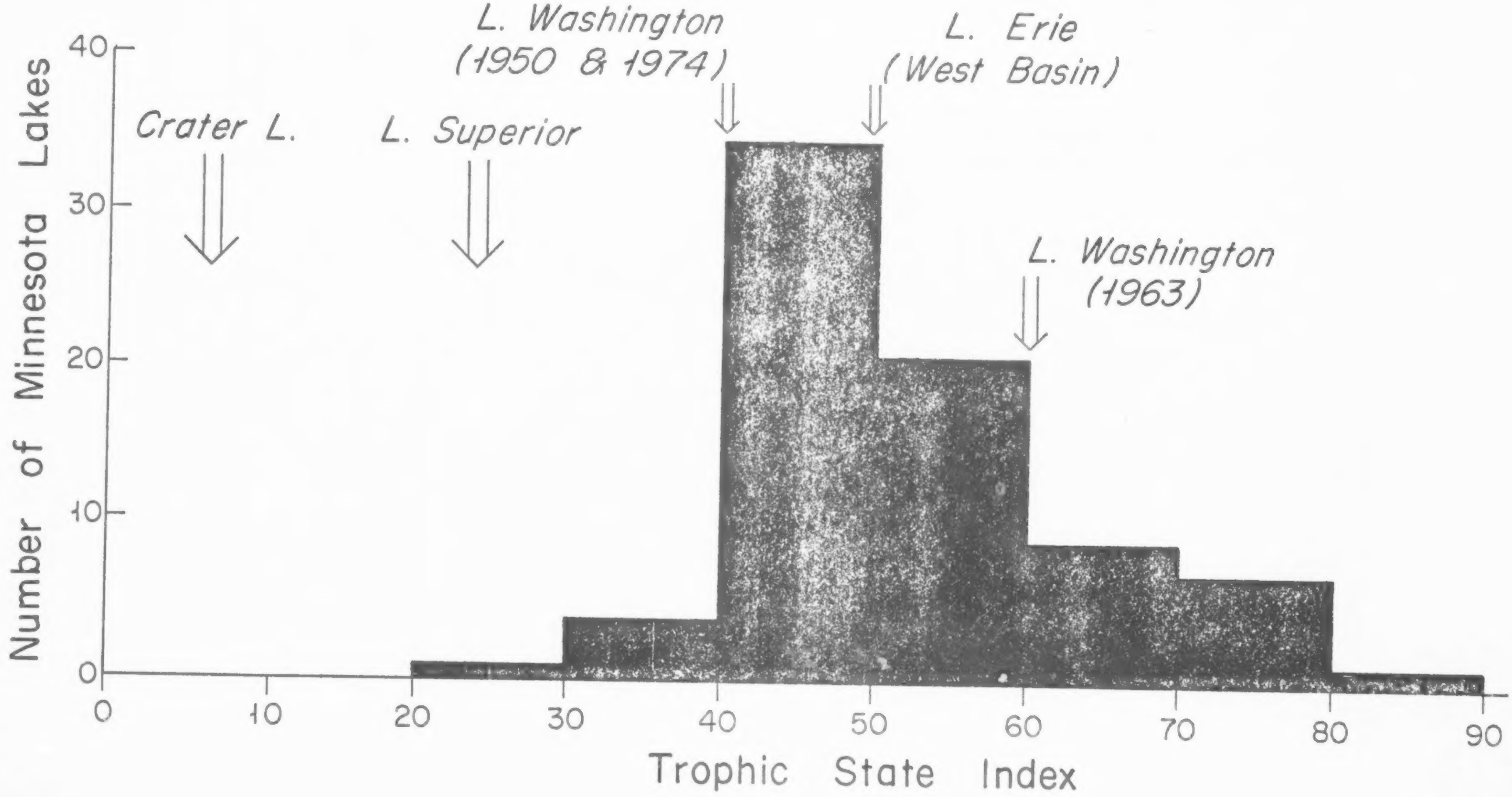

Figure 10. TSI values for a group of Minnesota lakes and for several other lakes.

The index also has value as an analytical tool. Note in figure 9 that the TSI values determined separately from the three parameters do not always coincide. This does not necessarily mean that the index values are wrong but may indicate instead certain facts about the lake's behavior. For example if the $TSI_{(TP)}$ is higher than the $TSI_{(SD)}$ or $TSI_{(CHL)}$ it could indicate that either the lake is not phosphorus limited, or that grazing by herbivorous zooplankton is important.

Postscript

The world is becoming quantitative. Of the indices described here more than half were developed since 1970. The reason is obvious. There is a need for quantitative indices to develop quantitative policies and to make national decisions based on quantitative considerations. There is also a need for scientists to communicate with each other and with the public in quantitative terms. Unless the limnological community takes its task seriously in selecting, quantifying, or developing specific indices to use on national and international scales the problem will soon become one of finding ways to translate the multitude of indices one to another. There is no single index that will satisfy every need but unless we are all prepared to compromise we will continue to flounder about in a mass of qualitative descriptions and the problems will get worse.

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TSI AND LCI: A COMPARISON OF TWO LAKE CLASSIFICATION TECHNIQUES

Paul D. Uttormark

Water Resources Center
University of Wisconsin
Madison, Wisconsin 53706

INTRODUCTION

In recent years increasing emphasis has been placed on the development and use of classification systems for lakes as an integral part of lake management efforts. By necessity, these systems must have minimal data requirements if they are to have broad application, because data are lacking for the majority of lakes. Two approaches proposed recently are based on the calculation of "Lake Condition Index" values (Uttormark and Wall, 1975) and "Trophic State Index" values (Carlson, 1974). It has been demonstrated that each of these indices can be a useful aid for communication and lake management decision-making. A volunteer lake monitoring program was initiated in Minnesota in 1973 in which lake residents collected Secchi depth data and lakes were classified according to the Trophic Status Index (TSI). This index was useful for comparing different lakes and, also, as a mechanism for communication with the general public (Shapiro, Lundquist and Carlson, 1975). In Wisconsin, the Lake Condition Index (LCI) was used to classify the 1150 larger lakes, and the results have also been incorporated into the planning and priority analysis of the state's lake protection and renovation program within the Department of Natural Resources (Uttormark and Wall, 1976). Significantly, the application and evaluation of these techniques have been limited to a single state, which limits the diversity of lake type, climatic influence, and public perception of water quality--factors which affect the usefulness and acceptability of classification results.

The purpose of this report is to apply the TSI and LCI classification methodologies to a diverse array of lakes representing a broad geographical area to determine whether under these conditions the two indices provide a similar measure of lake water quality, and whether they might be useful for comparing water quality conditions among these lakes. The objective is narrowly focused, and no attempt is made to assess the applicability of either technique under different circumstances or for other purposes. For this analysis, two types of comparisons were made between LCI and TSI values, based on a study set of about 200 lakes.

1. Both index values were calculated for each lake and a plot was prepared of Trophic State Index versus Lake Condition Index. (This was possible because each of the classification techniques is

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of the independent type--i.e., lakes are ranked according to an independent scale of reference, and individual classifications are not dependent on the rank of other lakes in the array.)

2. Each index is compared separately to the trophic categories selected by individuals who provided input data as best describing the character of each of the lakes in the study set.

It should be noted from the outset that there is no objective method for assessing the "accuracy" or "validity" of lake classification systems. At the root of the problem is the concept of trophic status which has never been quantified or defined precisely. Consequently, about the only method of checking classification results is to obtain subjective evaluations from individuals familiar with the subject lakes--i.e., determine whether the classification results agree with preconceived perceptions of lake status. This approach has considerable shortcomings, particularly when the study lakes are selected from a large geographical area over which there may be diverse variations in the perception of water quality. For a more comprehensive discussion of classification mechanics, system types and uses of classification results the reader is referred to Shapiro (1975) and Uttormark and Wall (1975).

LAKE CONDITION INDEX

A technique for computing "Lake Condition Indices," based on some of the more readily observable indicators of eutrophication, was proposed by Uttormark and Wall (1975). For this approach, points are assigned to lakes depending on the degree to which they exhibit undesirable symptoms of water quality. Four input parameters are used, and ranges of values for each parameter are specified to depict lake conditions ranging from desirable to undesirable. The parameters used and the range of possible points assigned are listed below.

Table 1. POINT SYSTEM
FOR LAKE CONDITION INDEX

Parameter	Points
Hypolimnetic dissolved oxygen	0-6
Transparency	0-4
Fishkills	0,4
Use impairment (extent of macrophyte or algal growths)	0-9
Total	0-23

The parameters are treated independently, and composite lake ratings are determined by summing the number of points assigned in each of the four categories. The sum is termed a "Lake Condition Index" (LCI). Thus, if a lake exhibited none of the specified undesirable symptoms of eutrophication, it received no points (LCI = 0). Conversely, for a lake to have an LCI of 23 it would have had to have all the undesirable characteristics in the most severe degree. Details of the classification methodology are given in the appendices.

LCI values were calculated for all (approx 1150) Wisconsin lakes with surface areas in excess of 100 acres (40 ha). In an attempt to check the "accuracy" of the results, lakes were listed regionally according to LCI value, and these lists were reviewed by area managers of the Wisconsin Department of Natural Resources. Of the 1150 lakes classified, 303 were reviewed in detail by the area managers. A summary of their critiques is given in Table 2.

Table 2. SUMMARY OF LCI REVIEW
BY WISCONSIN DNR AREA MANAGERS

Area number	Total lakes	LCI number unchanged	LCI number changed by 2 or less	LCI number changed by 3 or more
1	9	2	6	1
2	42	32	4	6
3	32	20	6	6
4	62	52	7	3
5	84	63	11	10
6	16	11	4	1
7	21	5	10	6
8	23	8	9	6
9	14	9	3	2
Totals	303(100%)	202(66%)	60(20%)	41(14%)

It was found that 202 (66%) of the LCI values reviewed were left unchanged; 60 scores (20%) were changed by 2 or fewer points; and only 41 scores (14%) were considered to be in error by 3 or more points. (As part of tests conducted early in the project, it was estimated that LCI values were reproducible to within ±2 units when different sources of input data were used to classify the same lakes.)

Based on these results, it was concluded that the technique worked reasonably well in Wisconsin considering that data were lacking for many of the subject lakes. The primary objective of the classification effort was to obtain an improved perspective of the lake resources of the state, and, for that purpose, the results appear to be useful and are being used to develop management strategies and priorities. It was suggested that this classification approach might be applicable in other states as well as in Wisconsin, as shown in Table 3.

Table 3. ESTIMATED APPLICABILITY OF THE LCI APPROACH[a]

	Number of lakes[b]
Direct applicability - Group 1	
Conn, Ill, Ind, Ia, Me, Mass, Mich, Minn, Neb, NH, NY, ND, Ohio, Penn, RI, SD, Vt, Wis	9,503
Some modification - Group 2	
Calif, Colo, Del, Ida, Kan, Ky, Md, Mo, Mont, Nev, NJ, NC, Okla, Ore, Tenn, Utah, Va, Wash, WVa, Wy	2,073
Major changes - Group 3	
Ala, Ariz, Ark, Fla, Ga, La, Miss, NM, SC, Tex	2,023
Total	13,599

[a] from Uttormark and Wall (1975)

[b] Based on a summary of lake inventory data compiled by individual states. Lakes larger than 100 surface acres.

TROPHIC STATUS INDEX

This classification was developed primarily as an aid for communication between limnologists and with the general public, and it is suggested that this index, or a modification of it, might serve as a replacement for the poorly-defined trophic categories which have been used traditionally (Shapiro, Lundquist and Carlson, 1975). The index is based on a single parameter, Secchi depth, and is defined as follows:

$$\mathrm{TSI} = 10(6 - \log_2(\mathrm{SD}))$$

where SD denotes the Secchi depth in meters. This logarithmic transformation results in a TSI increase of 10 units when the Secchi depth decreases by a factor of 2. (Corresponding values of Secchi depth and TSI are given in Table 4.)

Table 4. TROPHIC STATUS INDEX VALUES AS A FUNCTION OF SECCHI DEPTH

Secchi depth (meters)	TSI
64	0
32	10
16	20
8	30
4	40
2	50
1	60
0.5	70
0.25	80

Because of its simplicity, the TSI has many of the advantages of an "ideal" classification technique: data requirements are minimal, the index values are absolute, and the approach is objective. However, "trophic status" has traditionally been used as a multidimensional concept (Shannon and Brezonik, 1972), and one might question the amount of information that can be relayed on the basis of a single parameter. Nevertheless, it has been shown that, for many lakes, there is a definable relationship between Secchi depth and chlorophyll-a and between Secchi depth and total phosphorus (Shapiro, Lundquist and Carlson, 1975) and, alternately, the TSI may be defined in terms of these input parameters as well.

A volunteer data collection program was undertaken in Minnesota and, in 1975, 250 lakes were being monitored to obtain Secchi depth data. A frequency distribution for about 80 of these lakes showed that the TSI ranged from about 20 to 90 with the majority of lakes having TSI values between 40 and 60. The data plot approached a normal distribution. No attempt was made to compare the TSI rankings to the traditional trophic descriptions, nor were any names associated with specific ranges of the TSI. This is consistent with the objectives of the TSI development, in which an attempt is made to replace the traditional trophic groupings with a continuous index which, like the Richter scale for earthquakes, gains meaning and acceptance through use.

DATA COMPILATION AND ANALYSIS

To obtain the basic information necessary for this analysis, a data form was designed which contained provisions for the following information:

1. Lake identification, i.e., name, size, etc.
2. Condition characteristics - four questions relating to DO conditions and extent of "weed"/algal growth.
3. Secchi depths - three or more values obtained during the growing season.
4. Trophic status - whether, in the opinion of the responder, the lake is very oligotrophic, oligotrophic, mesotrophic, eutrophic, very eutrophic.

Data forms were mailed either to the state agency judged to have lake management responsibilities or to the Water Resources Research Institute in each state, and it was requested that information be provided for 10-12 lakes of differing trophic character. Only one source was contacted in each state.

Excellent cooperation was received in obtaining the desired lake information. Data sufficient to compute both TSI and LCI values were received from 21 states relating to more than 200 lakes. Also, partial information was received from an additional 5 states; unfortunately, time constraints did not permit the compilation of missing information so these data could not be incorporated into this report. A number of other states reported that it was not possible to provide the desired data because it was not available or because time/manpower constraints precluded compilation of the information. The data request was unacknowledged for only a few states.

Data analyses consisted of converting all the input data to consistent (metric) units, and computing the corresponding LCI and TSI index values. A tabulation of all the input data, as well as plots of TSI versus LCI values for each state, is given in the appendices.

It should be noted that all mathematical manipulations relating to the TSI were made on the Secchi data, not the corresponding index values. For example, Secchi depth data were averaged over the growing season and mean values were used to compute the TSI for each lake. (A different result would have been obtained if each Secchi value had been converted to a TSI and then averaged.) Likewise, frequency data and statistical summaries are based on Secchi data which were converted to TSI values only as a final step. However, all graphs are presented linearly with respect to TSI and, therefore, logarithmic with respect to Secchi depth.

RESULTS

A comparison of TSI and LCI values for each of the lakes in the data set is given in Figure 1. The open circles represent data for those states in which the LCI was estimated to apply directly (see Table 3), and the solid symbols refer to states in which the LCI was thought to apply only with modification. This data segregation was done in an attempt to eliminate one source of variation between the two indices. However, since the distribution for the three data groups showed considerable overlap, no further distinction of data groups is made here, and all the data are considered to be part of a single set.

In comparing TSI with LCI values it should be noted that Secchi depth is incorporated in both indices, and therefore some correlation is imposed by definition. For example, for an LCI of zero, the typical Secchi depth must exceed 7 meters. This is equivalent to a TSI of 32 or less.

If there is very good agreement between the two indices, then all the data points should fall in a narrow band from upper left to lower right in Figure 1. This band could have some type of curvature--a straight line would not be expected--but if the two indices yield similar measures of "status" or "condition," a distinct band should result. This was not the case. Considerable data scatter resulted when TSI was plotted against LCI. For a given LCI, TSI values cover a range of about 30-40 units; conversely, for a given TSI, LCI values spanned nearly the total possible LCI range. Clearly, the two indices are not indicative of similar characteristics for the lakes in this study set.

As a second measure of comparison, each of the indices was compared independently to the trophic category chosen by individuals who provided the input data for this analysis. Five trophic categories were provided--very oligotrophic, oligotrophic, mesotrophic, eutrophic and very eutrophic--and responders were asked to select the category which, in their opinions, best described the lake. No definitions were given for the different categories. (Several individuals pointed out that definitions would have been desirable; some indicated that more than one category could have been selected depending on whether the selection was

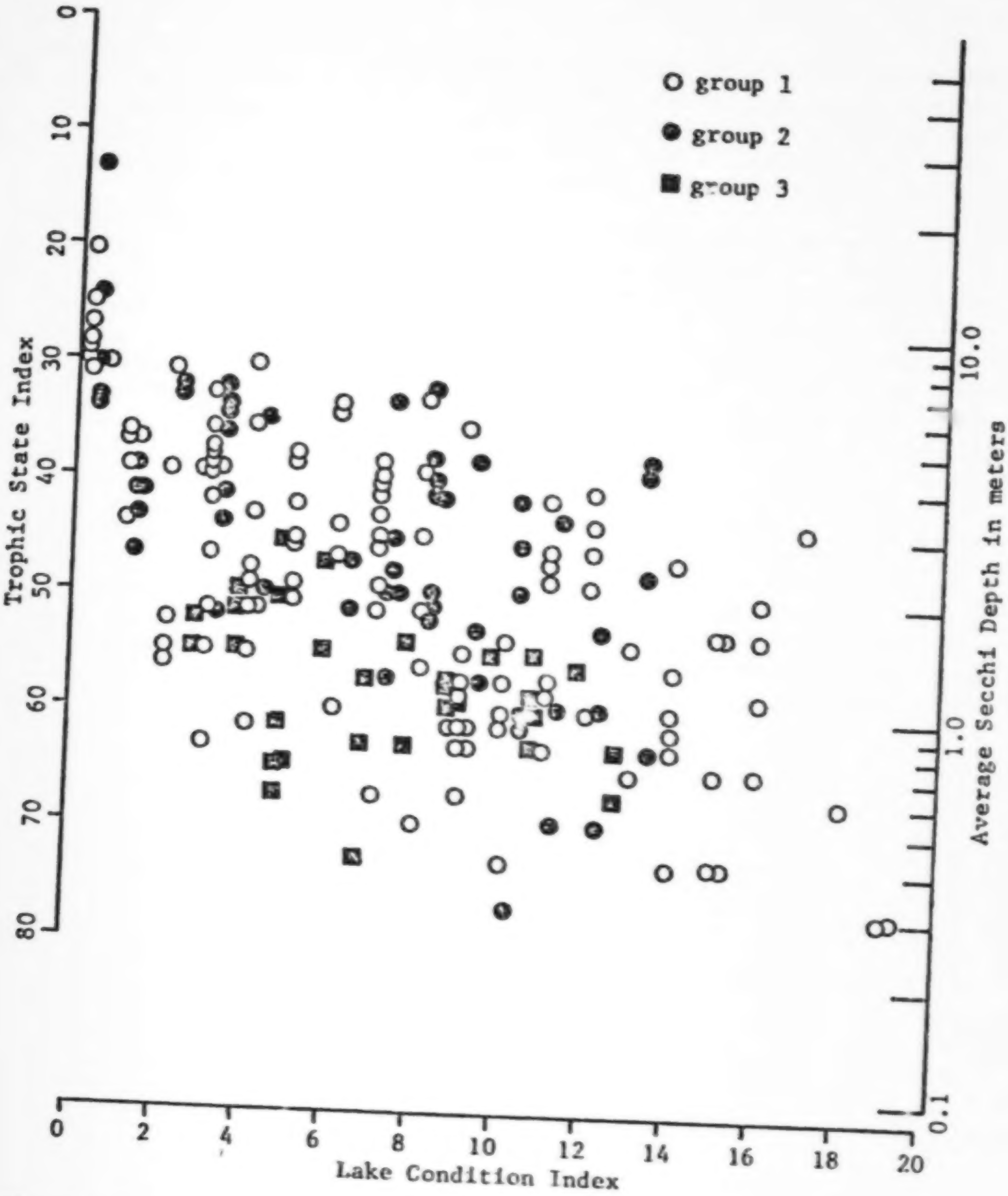

Figure 1: Comparison of Lake Condition Index to Trophic State Index values for the composite set of study lakes.

based on nutrient content, algal concentrations or oxygen conditions; and a few declined to select categories because definitions were lacking. These responses emphasize the need for quantification and improved methods for communication regarding lake characteristics and conditions.)

Frequency distributions for LCI and TSI values as compared to perceived trophic status of a composite of all lakes in the study set are given in Tables 5 and 6, respectively. The total number of lakes differs between the two tables because of incomplete data for some lakes. A plot showing the mean index values and the standard deviation about the mean for each of the five trophic categories is given in Figure 2. These data show that mean LCI and mean TSI values increase as the perceived trophic state progresses from very oligotrophic to very eutrophic; however, data scatter in both cases was fairly large. As shown by Tables 5 and 6, typically, a given LCI value spans 3 of the 5 trophic categories; a given TSI value typically spans 4 of the 5 categories. (Note that the selected trophic category for lakes having an average Secchi depth of 4-5 meters spanned the entire range from very oligotrophic to very eutrophic.)

Table 5. FREQUENCY DISTRIBUTION OF LCI VALUES AS COMPARED TO TROPHIC STATUS DESCRIBED BY RESPONDERS (COMPOSITE OF ALL LAKES)

Selected trophic category	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	No.	Ave	σ
VC	4	1		1																			6	0.6	1.2
O	5	5	5	7	4	2																	28	2.2	1.5
M		3	3	8	5	9	8	14	7	3	1	3	3	1									68	6.2	2.8
E				3	5	2	3	5	7	7	10	3	3	5	4	3	3	1					64	9.5	3.7
VE									2	5		2	3	1	2	2	1		1	2		1	22	12.9	3.9

Table 6. FREQUENCY DISTRIBUTION OF AVERAGE SECCHI DEPTHS AS COMPARED TO TROPHIC STATUS DESCRIBED BY RESPONDERS (COMPOSITE OF ALL LAKES)

	Trophic state index																	
					30			40		50	60	70	80					
	Average Secchi depth (meters)																	
Selected trophic category	11+	10-11	9-10	8-9	7-8	6-7	5-6	4-5	3-5	2-3	1-2	½-1	¼-½	-¼	No.	Ave (SD)	Ave (TSI)	σ (SD)
VO	1[a]				3		1	1							6	7.9	30.2	3.7
O	2				2	5	4	6	3	2	2				26	5.3	36.0	2.5
M		1			1	2	2	6	13	14	20	5			64	2.9	44.6	1.8
E						1	2	1	2	14	25	17	3		65	1.8	51.5	1.2
VE								2	2		6	6	6		22	1.4	55.1	1.3

[a] Lake Tahoe (SD = 25.6) not included in calculations

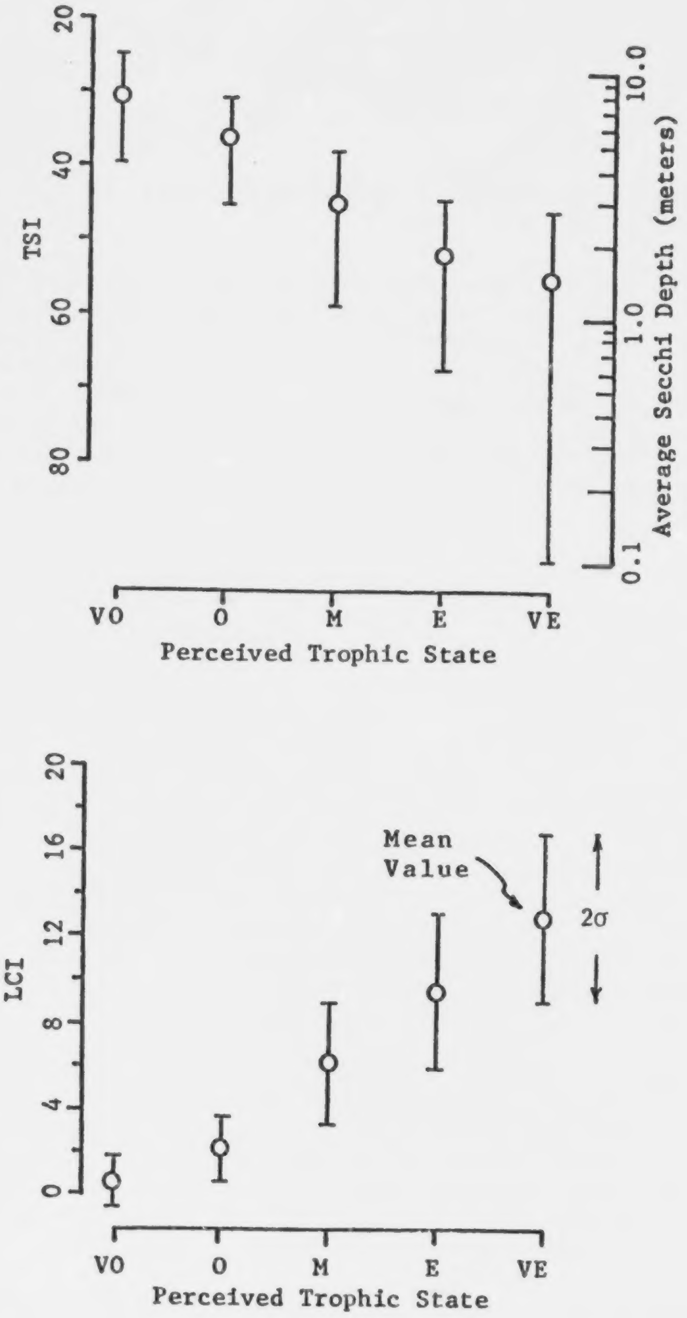

Figure 2: Comparison of mean TSI and mean LCI values to the trophic state of the composite study lakes as described by responders in the various states. (Very oligotrophic, oligotrophic, mesotrophic, eutrophic, very eutrophic)

SUMMARY AND CONCLUSIONS

A comparison of LCI and TSI values for a study set of more than 200 lakes distributed through the United States showed little agreement between the two indices. A value of one index cannot be inferred from knowledge of the other. Even though Secchi depth, the sole input parameter for the TSI, is also included in the LCI, the inclusion of information relating to dissolved oxygen, fishkills and abundance of macrophyte and/or algae, masks the interdependence of the two indices.

Both the LCI and TSI indices were compared to subgroups of the original data set after it had been divided into 5 subsets according to the trophic categories selected by the individuals who provided the lake data. The mean values of each index increased as the trophic category progressed from very oligotrophic to very eutrophic, however significant data scatter resulted within each group. This was due only in part to the inability of the classification techniques to cleanly sort the data set--of at least equal importance are the differences in definition of the traditional trophic categories from individual to individual, differences which are exaggerated when lakes from a large geographical area are considered simultaneously. The comparisons conducted here demonstrate clearly the communication difficulties associated with describing lakes according to the traditional trophic categories.

The TSI approach results in a ranking of lakes according to mean Secchi depth. The ranking is objective and is not influenced by regional differences in terminology. However, it was found that lakes of widely differing character may have similar mean Secchi depth, and it is not clear that more information would be conveyed if TSI values rather than trophic categories were used.

The LCI approach results in a ranking of lakes according to several parameters which are considered to be additive. Consequently, a given LCI may result from different combinations of the input parameters. This does not appear to induce excessive diversity within LCI ranks when the system is applied to lakes in a homogeneous climatic region; however, when the region spans the continental United States, diversity within ranks becomes larger.

It has been demonstrated that both the TSI (in Minnesota) and the LCI (in Wisconsin) can be used as effective tools for communication and decision-making when they are applied under more restrictive conditions than those reported here. This is a step in the right direction. Improved techniques for describing lake characteristics are needed, and continuing efforts should be made to quantify and define more precisely trophic terminology and concepts.

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Appendix 1

METHODOLOGY FOR CALCULATING LAKE CONDITION INDEX VALUES

The technique is based on the assignment of "penalty points" to lakes depending on the degree to which they exhibit undesirable symptoms of eutrophication. Four parameters were selected for analysis, and ranges of values for each parameter were specified which depicted lake conditions ranging from desirable to undesirable. The parameters used and the range of possible points assigned are listed below.

POINT SYSTEM
FOR LAKE CONDITION INDEX

Parameter	Points
Dissolved oxygen	0-6
Transparency	0-4
Fishkills	0,4
Use impairment	0-9
Total	0-23

The parameters were treated independently, and composite lake ratings were determined by summing the number of points assigned in each of the four categories. The sum is termed a "Lake Condition Index" (LCI).

Dissolved oxygen in the hypolimnion was selected as one parameter for consideration because depletion of hypolimnetic oxygen supplies reflects the integral effect of many lake processes. The classification methodology for DO was based on the minimum conditions which were expected to occur in the hypolimnion during the stratified period. Points were assigned in the following manner:

	Penalty points	
Dissolved oxygen conditions	Max depth <30'	Max depth >30'
Dissolved oxygen in hypolimnion greater than 5 ppm at virtually all times	0	0
Concentrations in hypolimnion less than 5 ppm but greater than 0 ppm	1	2
Portions of hypolimnion void of oxygen at times	3	4
Entire hypolimnion void of oxygen at times	5	6

As noted in the tabulation above, lake morphometry was taken into account in an approximate way by assigning more points to the deeper lakes. The breakpoint of 30 ft (10 m) maximum depth was selected arbitrarily as an indicator of lake basin geometry, which separates lakes with "large" or "small" hypolimnetic volumes as compared to the volume of the epilimnion. Lakes which do not stratify can receive few or no penalty points for dissolved oxygen conditions.

Secchi disk transparency was incorporated into the system by using typical annual maximum and minimum Secchi depths. Ranges rather than specific values were used.

Range	Typical Secchi depth
1)	0 - 1.5 ft (0 - 0.5 m)
2)	1.5 - 10 ft (0.5 - 3 m)
3)	10 - 23 ft (3 - 7 m)
4)	- >23 ft (>7 m)

The first range represents a condition in which light penetration would be severely limited. Within the second range, the depth of the photic zone is likely to be less than the depth of the epilimnion. Conversely, Secchi depths within the third range are indicative of a photic zone which extends below the epilimnion except for large lakes.

Points were assigned according to the combination of depth ranges which encompass the typical maximum and minimum Secchi depths. In the tabulation below, the above-listed range numbers of 1-4 are used: (Note: A provision is also included to cover the possibility that only one range of Secchi depths would be given.)

Transparency conditions if both ranges are given

Minimum range	Maximum range	Penalty points
1	1	4
1	2	3
1	3	2
1	4	2
2	2	2
2	3	1
2	4	0
3	3	0
3	4	0

Transparency conditions if only one range is given

Secchi depth range	Penalty points
1	4
2	2
3	1
4	0

The occurrence of fishkills was considered in the classification system, but no attempt was made to stipulate frequency or severity. Lake depth was taken into account however, and 30 ft (10 m) was again used as the breakpoint.

History of fishkills	Penalty points
None	0
Yes, max depth <30'	3
Yes, max depth >30'	4

The presence of algal blooms and excessive rooted aquatic vegetation was approached indirectly through information describing the severity of recreational use impairment due to the overadundance of these aquatic plants.

Lakes were penalized least heavily for problems resulting from "weed" growths; lakes having both "weed" and algae problems were penalized most severely. This was based on the rationale that algal blooms often affect an entire lake whereas the effect of rooted aquatic vegetation is normally restricted to the periphery. Also, rooted vegetation is sometimes more indicative of lake morphometry than water quality conditions.

Recreational Use Impairment

	Penalty points		
	Weeds only	Algae only	Weeds & algae
No impairment of use			
Very few algae present, no "bloom" conditions AND/OR Very few weeds in littoral zone	0	0	0
Slight impairment of use			
Occasional "blooms," primarily green species of algae AND/OR Moderate weed growth in the littoral zone	2	2	2
Periodic impairment of use			
Occasional "blooms," predominantly bluegreen species AND/OR Heavy weed growth in littoral zone	3	4	5
Severe impairment of use			
Heavy "blooms" and mats occur frequently, bluegreen species dominate AND/OR Excessive weed growth over entire littoral zone	6	7	9

Lake Condition Indices were calculated by summing the points received in each of the four categories. Thus, if a lake exhibits none of the specified undesirable symptoms of eutrophication, it would receive no points (LCI = 0). Conversely, for a lake to receive an LCI of 23 it would have to have all the undesirable characteristics in the most severe degree.

Appendix 2. TABULATED DATA FOR STUDY LAKES

Lake name	Area (ha)	Depth (m)		LCI points					Secchi depth (m)			Trophic state*
		Max	Mean	DO	TRNS	FSKL	IMPR	LCI	Ave	Max	Min	
California												
Casitas	1,100	86.9	28.6	2	2	0	2	6	2.4	-	-	E
Don Pedro	5,245	156.	47.5	0	1	0	0	1	3.1	4.3	2.1	M
Elsinore	1,050	3.7	-	0	3	3	4	10	0.3	0.5	0.3	E
Iron Gate	413	39.9	17.4	2	2	4	4	12	1.6	2.7	0.6	M
Lopez	20,600	45.1	16.8	4	1	4	4	13	4.6	-	-	M
Lower Twin	152	45.4	15.2	0	1	0	2	3	5.5	5.8	5.2	O
Nicasio	342	35.1	7.9	0	3	4	4	11	0.5	0.6	0.3	E
Pillsbury	811	36.6	14.3	0	3	4	4	11	1.0	1.8	0.2	M
Tahoe	48,600	501.	302.	0	0	0	0	0	25.6	27.6	23.1	O
Shasta	11,940	136.	46.3	0	1	0	0	1	3.7	5.2	2.4	M
Silver	45	19.2	-	0	1	0	0	1	3.7	4.1	3.2	O
Upper Twin	107	34.1	14.3	0	0	0	2	2	6.6	7.9	5.8	O
Colorado												
Canter	455	52.	29.	0	1	0	0	1	2.5	4.0	1.7	M
Estes	75	15.	5.	4	1	0	2	7	2.0	3.5	1.0	M
Granby	2,542	60.	19.	2	1	0	4	7	2.3	3.2	1.6	M
Grand	205	81.	41.	4	1	0	3	8	1.8	3.2	1.5	M
Green Mountain	820	74.	21.	2	1	0	0	3	1.7	5.3	0.9	M
Horsetooth	755	62.	24.	4	1	0	4	9	1.6	2.3	1.0	E
Lower Agnes	7.8	20.	-	0	0	0	0	0	6.2	8.2	4.3	O
Rawah #3	-	-	-	2	1	0	0	3	5.1	6.2	4.2	VO
Rhadam Mountain	548	11.	4.	0	2	0	4	6	1.8	2.5	1.0	M
Sugarbowl	3.2	16.	-	2	2	0	0	4	2.0	2.2	1.8	M
Summit	12	15.	-	0	1	0	0	1	4.2	5.0	3.6	VO
Upper Camp	15	25.	-	2	1	0	0	3	3.6	5.0	2.6	O

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* Trophic state as described by responders

Appendix 2. Con't

Lake name	Area (ha)	Depth (m)		LCI points				LCI	Secchi depth (m)			Trophic state*
		Max	Mean	DO	TRNS	FSKL	IMPR		Ave	Max	Min	
Georgia												
Allatoona	4,800	44.2	9.4	4	2	0	2	8	1.5	1.7	1.1	M
Brantley	18	6.1	3.0	1	2	0	2	5	0.7	0.7	0.6	E
Chief McIntosh	56	6.0	3.0	1	2	0	0	3	1.4	2.2	0.8	M
Clark Hill	28,300	43.0	10.9	2	2	0	0	4	1.4	1.9	1.0	M
Fort Yargo	97	9.8	4.0	1	2	0	0	3	1.7	1.8	1.4	M
Hartwell	24,830	54.9	14.0	2	2	0	0	4	2.0	2.4	1.8	O
High Falls	243	7.3	3.7	3	2	0	4	9	1.1	1.4	0.9	E
Jackson	1,922	27.0	6.9	4	2	0	7	13	0.8	1.0	0.4	E
Seminole	15,200	8.5	3.0	1	2	0	3	6	1.4	2.1	0.9	M
Tobeoskfee	708	13.7	-	4	2	0	4	10	1.4	1.3	1.4	E
Union	8	16.8	6.0	2	2	0	0	4	1.8	-	-	O
West Point[a]	10,500	27.4	7.3	4	2	4	2	12	1.3	1.4	0.9	E

[a] 1-year-old impoundment

Lake name	Area (ha)	Depth (m)		LCI points				LCI	Secchi depth (m)			Trophic state*
		Max	Mean	DO	TRNS	FSKL	IMPR		Ave	Max	Min	
Illinois												
Baldwin	800	12.2	3.1	2	2	0	2	6	1.0	1.2	0.9	E
Bloomington[a]	197	10.7	5.0	2	3	0	0	5	0.9	1.8	0.5	E
Cedar	115	10.7	1.2	2	2	0	2	6	2.5	3.0	1.8	M
Decator[a]	114	4.6	1.4	1	3	0	2	6	0.5	0.6	0.4	E
East Loon	67	6.4	1.8	3	2	0	3	8	1.3	1.5	0.9	E
Highland Silver[a]	299	7.3	4.2	1	3	0	2	6	0.3	0.4	0.2	E
Lou Yaeger[a]	572	6.7	3.3	1	4	0	-	-	0.2	0.4	0.1	E
Slocum	77	1.5	1.2	3	4	3	9	19	0.3	0.4	0.2	VE
Springfield[a]	1,731	6.1	4.0	1	3	0	2	6	0.4	0.6	0.2	E
Story	53	7.2	4.6	3	2	0	5	10	1.0	1.4	0.8	E
Vermilion[a]	283	4.6	1.4	3	3	0	0	6	0.4	0.6	0.4	E
Wonder	295	4.	2.5	0	3	3	9	15	0.4	0.5	0.2	VE

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[a] Turbidity due to suspended inorganic material

Appendix 2. Con't

Lake name	Area (ha)	Depth (m)		LCI points				LCI	Secchi depth (m)			Trophic state*
		Max	Mean	DO	TRNS	FSKL	IMPR		Ave	Max	Min	
Maine												
Branch	1,093	37.8	9.6	0	0	0	0	0	8.2	9.0	6.4	
Brettous	62	12.8	5.5	2	1	0	0	3	4.0	6:1	3.0	
Coffee	55	21.3	10.1	0	0	0	0	0	8.7	10.0	7.5	
Eagle	2,258	42.6	13.7	2	1	0	0	3	4.4	5.6	2.8	
Hopkins	178	19.8	6.7	0	0	0	0	0	7.5	9.1	5.0	
Minnehonk	40	22.3	9.1	0	1	0	0	1	4.8	5.9	3.7	
Phillips	335	32.0	9.4	0	0	0	0	0	7.7	9.1	5.2	
Pleasant	741	20.4	9.6	0	0	0	0	0	9.7	11.6	6.2	
Portage	1,001	7.6	2.4	0	1	0	0	1	3.0	3.4	2.7	
Pushaw	2,046	8.5	3.0	1	1	0	2	4	3.2	3.7	2.1	
Raymond	140	12.8	4.9	-	1	0	0	-	5.2	6.2	4.3	
Wilson	194	26.8	8.2	2	1	0	0	3	4.6	5.9	2.4	
Maryland												
Deep Creek	1,578	21.9	8.1	2	1	0	0	3	3.0	4.3	1.8	M
Johnson	42	6.1	2.1	0	2	0	5	7	1.2	1.8	0.8	E
Liberty	1,259	43.3	12.7	2	1	0	4	7	2.8	5.5	0.5	M
Loch Raven	767	21.3	15.2	2	2	0	4	8	1.7	3.0	0.5	E

Appendix 2. Con't

Lake name	Area (ha)	Depth (m)		LCI points				LCI	Secchi depth (m)			Trophic state*
		Max	Mean	DO	TRNS	FSKL	IMPR		Ave	Max	Min	
Massachusetts												
Indian	78	5.5	3.1	1	2	3	5	11	1.2	1.7	0.9	M
Mattawa	45	10.7	-	2	1	0	0	3	4.1	4.7	3.5	O
Norton	214	2.5	1.0	0	3	3	9	15	0.4	0.5	0.3	VE
Nutting	32	2.4	1.3	0	3	0	6	9	0.8	1.3	0.3	E
Pearl	88	10.7	3.7	4	1	4	3	12	3.8	4.4	3.0	M
Pontoosuc	189	10.7	4.3	4	2	0	3	9	2.2	2.9	1.7	E
Quaboag	215	3.7	1.8	0	2	0	0	2	1.7	2.1	1.5	O
Quacumquasit	88	21.9	9.9	4	1	0	0	5	4.3	5.5	3.0	M
Upper Mystic	68	25.0	8.5	6	2	4	4	16	1.6	2.6	0.8	E
Waushakum	33	16.2	4.3	4	1	4	3	12	3.1	3.7	2.9	M
Michigan												
Bear	128	18.3	-	2	0	0	0	2	7.4	8.5	6.6	O
Cass	518	39.0	-	2	1	0	2	5	2.6	4.1	1.7	M
Elk	3,128	58.5	-	0	1	0	0	1	4.8	3.0	6.7	O
Coguac	352	20.1	-	4	2	0	2	8	2.8	3.2	2.1	M
Higgins	3,885	40.5	-	0	0	0	0	0	7.3	9.8	4.3	VO
Kent	405	11.6	-	2	2	0	5	9	1.4	2.1	0.8	VE
Lansing	183	10.7	-	4	2	4	3	13	1.5	2.3	1.0	E
Orchard	318	33.5	-	4	1	0	0	5	3.4	4.3	2.4	O-M
Silver	243	29.3	-	4	0	0	2	6	6.1	7.6	2.9	M

Appendix 2. Con't

Lake name	Area (ha)	Depth (m)		LCI points				LCI	Secchi depth (m)			Trophic state*
		Max	Mean	DO	TRNS	FSKL	IMPR		Ave	Max	Min	
Mississippi												
Clark	25	2.4	1.5	5	2	0	2	9	0.9	1.2	0.8	
Claude Bennett	29	3.7	1.7	5	2	0	4	11	0.8	1.4	0.3	
Columbia	36	3.0	1.5	5	2	0	2	9	1.0	1.1	0.8	
Jeff Davis	66	5.5	2.6	5	2	0	4	11	1.0	1.2	0.9	
Monroe	45	4.9	2.1	5	2	0	4	11	0.8	1.4	0.3	
Perry	51	7.9	2.4	5	2	0	0	7	1.2	1.9	0.6	
Roosevelt	51	3.7	2.4	5	2	0	2	9	0.9	1.5	0.3	
Ross Barnett	35	4.6	2.4	5	2	0	4	11	1.1	1.1	1.1	
Tippah	61	5.5	3.0	5	2	0	2	9	1.2	1.4	1.1	
Tombigbee	33	3.7	2.1	5	2	0	4	11	1.1	2.1	0.7	
Walthall	25	4.3	2.4	5	2	0	4	11	1.4	2.2	0.8	
Montana												
Ashley	1,134	61.	27.	0	0	0	2	2	10.0	11.9	6.6	M
Blaine	151	42.7	16.	0	0	0	0	0	5.9	7.0	4.6	E(?)
Blanchard	59	9.8	3.5	2	1	0	6	9	4.4	4.6	4.3	VE
Echo	233	21.	5.5	2	0	0	5	7	6.3	8.5	4.0	E
Five	95	18.9	5.4	2	1	0	0	3	5.4	6.4	4.0	E
Foy	110	40.	16.	2	0	0	6	8	3.6	7.3	1.2	VE
Little Bitterroot	1,224	85.	31.	0	0	0	0	0	11.9	13.7	9.8	O
Lower Stillwater	100	15.8	4.4	4	2	0	2	8	4.5	6.1	0.1	E
Mary Ronan	609	14.3	8.6	2	1	4	6	13	4.3	7.0	3.1	VE
Rogers	96	5.8	2.7	1	1	0	6	8	3.9	4.6	3.4	VE
Swan	1,328	40.2	18.	0	2	0	2	4	5.7	8.5	0.3	M
Whitefish	1,356	67.1	33.	0	1	0	2	3	6.9	11.0	1.5	O

Appendix 2. Con't

Lake name	Area (ha)	Depth (m)		LCI points				LCI	Secchi depth (m)			Trophic state*
		Max	Mean	DO	TRNS	FSKL	IMPR		Ave	Max	Min	
Nebraska												
Branched Oak	728	8.	4.4	0	2	3	5	10	1.5	4.1	0.5	E
Holmes[a]	45	4.	1.9	0	4	0	0	4	0.3	0.6	0.2	M-E
McConaughy	14,160	50.	-	4	1	0	2	7	3.2	5.0	1.5	M-E
Pawnee	299	8.	3.7	0	2	0	9	11	1.1	3.9	0.4	VE
Stagecoach	79	5.	3.0	0	2	0	9	11	0.8	2.5	0.3	VE
Wagon Train[a]	127	6.	2.6	0	3	0	0	3	0.5	1.0	0.2	E
New Hampshire												
Glen	48	16.8	8.5	2	2	0	4	8	1.8	2.7	1.1	E
Hot Hole	13	13.1	5.7	6	1	0	0	7	3.8	4.0	3.4	M
Kezar	73	8.2	-	5	2	0	7	14	0.9	1.2	0.6	E
Mascoma	451	20.7	-	2	1	0	4	7	3.6	5.2	2.4	M
Newfound	1,662	51.2	19.8	0	0	0	0	0	7.3	7.6	7.0	VO
Ossipee	1,251	18.6	-	2	1	0	0	3	4.2	4.4	3.7	O
Pleasant	200	19.5	-	4	0	0	0	4	7.9	9.8	6.1	M
Province	410	5.2	3.7	0	2	0	5	7	2.1	2.7	1.5	E
Rocky Bound	26	9.4	6.4	0	1	0	0	1	5.0	5.2	4.9	O
Sunapee	1,642	43.3	-	2	1	0	0	3	6.6	6.7	6.4	O
Wentworth	1,221	29.9	-	2	1	0	0	3	5.3	5.5	5.2	O
Winnisquam	1,725	51.8	15.8	4	1	0	4	9	5.5	8.1	2.7	E

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[a] Turbidity due to suspended inorganic materials

Appendix 2. Con't

Lake name	Area (ha)	Depth (m)		LCI points				LCI	Secchi depth (m)			Trophic state*
		Max	Mean	DO	TRNS	FSKL	IMPR		Ave	Max	Min	
New Mexico												
Abiquiu	526	27.4	10.7	2	3	0	4	9				M
Bill Evans	25	18.3	12.2	2	3	0	2	7				M
Bonito	18	12.8	8.3	2	2	0	2	6				M
Caballo	2,430	15.2	6.1	2	3	0	0	5				M
✓Elephant Butte	4,000-8,000	46.	18.	2	3	4	4	13	0.6	1.0	0.3	M
Fenton	7	8.5	3.0	3	3	3	9	18				E
Heron	1,415	36.6	15.2	0	1	0	0	1				O
Navoja	5,260	76.2	42.7	0	0	0	0	0				O
Nogal	12	3.3	1.5	1	3	3	6	13				E
Snow	40	18.3	5.5	4	3	4	7	18				M
✓Ute	1,620	24.4	9.1	2	3	0	0	5				M
Wall	7	6.1	3.4	1	3	0	3	7				M
New York												
Canadarago	1,022	13.4	7.5	6	2	4	4	16	2.0	3.0	1.1	E
Clear	40	20.4	10.1	0	0	0	0	0	15.0			VO
Conesus	1,214	20.1	10.7	4	0	0	2	6	5.8	6.5	5.0	M
George	11,400	58.	18.	0	0	0	0	0	11.1	13.5	8.5	O
Greenwood	777	17.4	-	4	1	4	3	12	2.6	4.0	1.2	E
Neversink	471	50.0	18.3	0	1	0	0	1	4.2	4.6	3.7	O
Oneida	20,700	16.8	6.8	4	2	0	2	8	4.1	4.9	3.0	M
Raquette	2	31.4	6.1	0	1	0	0	1				O
Swinging Bridge	405	36.6	13.7	4	2	4	4	14	1.3	2.1	0.9	E
Upper Saranac	2,059	30.5	-	2	1	0	2	5	2.1	2.1	2.0	M

Appendix 2. Con't

Lake name	Area (ha)	Depth (m)		LCI points				LCI	Secchi depth (m)			Trophic state*
		Max	Mean	DO	TRNS	FSKL	IMPR		Ave	Max	Min	
North Dakota												
Crown Butte	13	9.4	3.8	4	3	4	5	16	1.1	1.8	0.3	E
Dion	34	6.4	3.8	3	2	3	3	11	2.4	3.0	1.4	E
Gravel	40	6.7	4.0	3	2	3	3	11	2.6	3.5	1.0	E
Hooker	14	8.3	4.4	5	3	3	5	16	0.7	0.9	0.3	VE
Moon	35	12.8	5.0	4	1	4	2	11	3.6	2.8	4.3	
Sakakawea	149,021	54.9	18.9	0	2	0	2	4	2.1	4.0	0.2	O
School Section	140	4.4	3.0	5	2	3	2	12	2.1	3.0	0.6	E
Sweetbriar	110	8.5	2.9	1	3	0	5	9	0.6	1.3	0.3	VE
Upsilon	168	8.2	3.4	5	3	3	4	15	0.7	1.1	0.3	E
Ohio												
Action	102	10.7	4.0	4	3	0	3	10	0.4	0.6	0.3	E
Berlin	1,477	21.3	5.0	4	3	0	2	9	0.9	1.3	0.5	E
Burr Oak	267	11.3	4.3	4	3	-	2	-	1.1	1.5	0.6	M
Camden	4	4.3	2.3	3	3	0	3	9	0.9	1.0	0.8	VE
Findlay #2	259	8.7	7.2	3	1	0	3	7	2.8	3.5	2.4	M
Forked Run	43	10.7	3.7	4	3	0	0	7	1.8	2.3	1.2	M
Hargus	59	17.1	9.1	4	3	0	2	9	1.1	1.4	0.7	M
Kiser	156	4.0	2.4	3	3	0	2	8	0.5	0.6	0.5	E
Long	91	13.7	5.0	4	3	0	3	10	0.9	0.9	0.9	E
Nettle	38	8.5	6.1	3	3	0	3	9	0.8	0.9	0.6	M
Paint Creek	473	15.2	5.3	4	3	0	2	9	0.9	2.1	0.2	

Appendix 2. Con't

Lake name	Area (ha)	Depth (m)		LCI points				LCI	Secchi depth (m)			Trophic state*
		Max	Mean	DO	TRNS	FSKL	IMPR		Ave	Max	Min	
Oklahoma												
American Horse	40.5	22.9	6.7	2	1	0	7	10	0.9	2.1	0.4	E
Ellsworth	2,260	16.5	5.1	0	3	0	2	5	-	-	-	M
Eufaula	41,500	26.5	7.1	4	3	0	0	7	-	-	-	M
Ft. Cobb	1,660	16.2	6.0	0	3	0	3	6	-	-	-	E
Grand	18,800	36.6	10.7	4	2	0	0	6	-	-	-	M
Greenleaf	370	14.3	4.9	4	3	0	3	10	1.0	2.7	0.3	M
Tenkiller	5,120	46.0	15.5	4	1	4	0	9	1.2	-	-	M
Watonga	22.3	7.9	3.6	4	2	0	7	13	0.8	1.5	0.3	E
Pennsylvania												
Allegheny	4,877	39.0	14.4	0	3	0	0	3	1.8	4.6	0.5	E
Beaver Run	455	18.3	7.3	2	2	0	2	6	3.0	4.6	2.1	M
Beltzville	383	36.9	12.8	2	1	0	0	3	3.5	4.6	2.7	M
Blanchard	700	9.4	1.6	3	2	0	4	9	1.2	2.2	0.6	VE
Canadohta	69	14.3	8.8	4	2	0	-	-	1.6	1.8	1.2	E
Conewago	138	5.2	2.7	3	2	0	5	10	1.2	2.1	0.5	E
Conneaut	378	20.1	7.3	4	2	4	4	14	2.5	2.7	2.0	E
Greenlane	329	18.9	5.0	2	3	0	9	14	1.0	1.8	0.5	VE
Harveys	267	29.3	11.0	2	1	0	0	3	4.1	5.8	3.0	M
Indian	304	18.3	4.3	2	1	0	0	3	2.5	3.7	1.8	M
Naomi	202	4.9	0.9	0	2	0	0	2	1.4	1.5	1.3	M
Ontelaunee	438	9.4	3.4	2	3	0	9	14	0.8	1.1	0.3	E
Pocona	304	7.9	3.7	1	2	0	0	3	1.4	2.4	0.8	M
Pymatuning	6,645	7.6	3.7	0	3	0	0	3	0.6	1.7	0.4	E
Shenango	1,441	10.7	2.5	2	2	0	-	-	0.9	1.2	0.6	E
Stillwater	141	2.4	1.0	0	2	0	0	2	1.3	1.5	0.8	M
Wallenpaupack	2,331	13.4	8.5	4	1	0	0	5	2.7	4.9	1.4	M

Appendix 2. Con't

Lake name	Area (ha)	Depth (m)		LCI points					Secchi depth (m)			Trophic state*
		Max	Mean	DO	TRNS	FSKL	IMPR	LCI	Ave	Max	Min	
South Carolina[a]												
Clark Hill	31,800	44.2	11.0	4	1	0	0	5	1.9	2.5	1.5	M
Fishing Creek	1,360	24.4	7.3	2	3	0	2	7	0.4	0.7	0.1	E
Greenwood	4,600	21.3	7.0	4	3	0	0	7	0.8	1.1	0.4	M
Hartwell	24,830	53.3	14.0	4	1	0	0	5	2.7	3.6	1.8	M
Marion	44,760	10.8	4.0	2	3	0	3	8	0.8	1.2	0.5	E
Moultrie	24,450	19.8	6.1	0	2	0	3	5	0.9	1.4	0.3	
Murray	20,600	54.9	12.5	4	2	0	0	6	2.4	2.7	1.8	M
Robinson	910	12.2	4.3	2	2	0	5	9	1.0	1.2	0.9	E
Saluda	200	12.2	4.0	0	3	0	2	5	0.7	0.9	0.5	M
Wateree	5,548	24.4	7.0	2	3	0	0	5	0.6	0.8	0.3	M

---

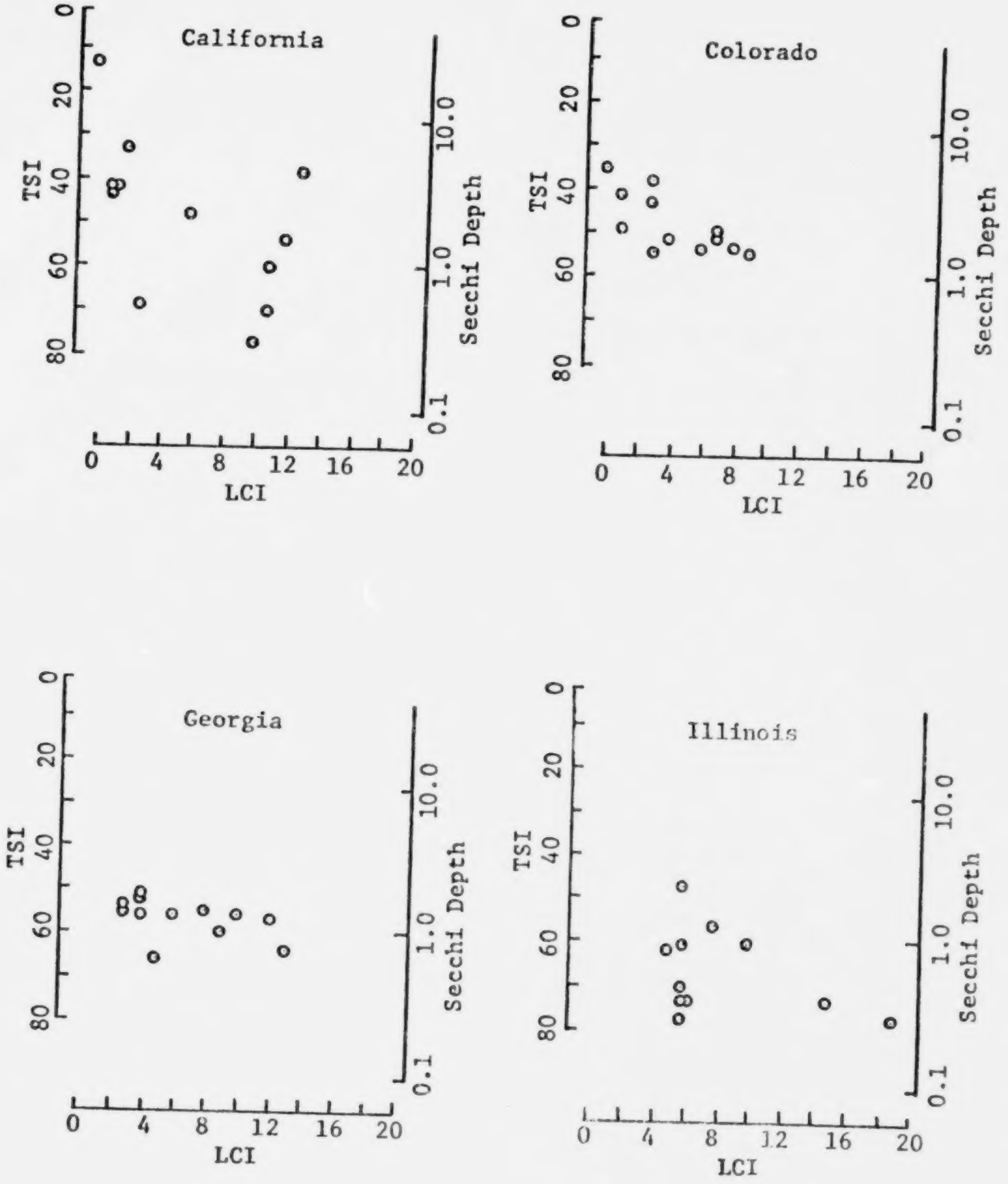
[a] Most turbidity due to suspended inorganic material

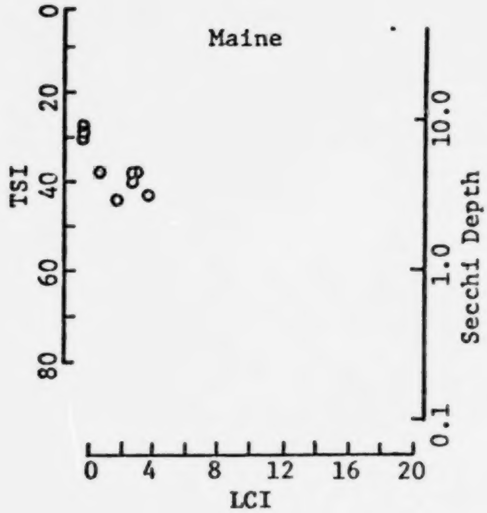
Lake name	Area (ha)	Depth (m) Max	Depth (m) Mean	DO	TRNS	FSKL	IMPR	LCI	Ave	Max	Min	Trophic state*
South Dakota												
Big Stone	5,107	4.9	3.4	0	3	0	9	12	1.0	2.7	0.4	VE
Clear	441	6.1	3.7	0	2	0	2	4	1.8	2.6	1.0	E
Cochrane	148	8.2	3.4	0	2	0	2	4	1.4	2.5	0.8	E
East Oakwood	405	2.7	1.5	3	3	3	5	14	0.4	0.5	0.3	VE
Enemy Swim	868	7.9	3.0	0	2	0	2	4	0.9	2.2	1.1	E
Hendricks	630	2.4	1.8	3	4	3	9	19	0.3	0.5	0.2	VE
Herman	546	2.1	1.2	3	3	3	9	18	0.6	1.6	0.2	VE
Kampeska	1,943	4.0	2.5	0	3	0	4	7	0.6	0.9	0.4	E
Norden	302	4.6	2.1	5	4	3	9	21	0.3	0.3	0.3	VE
Pickerel	386	13.2	6.1	0	2	0	2	4	2.3	5.2	1.2	E
Roy	685	5.6	3.3	0	2	0	3	5	1.9	2.5	1.6	E
South Red Iron	251	4.6	2.1	0	2	0	2	4	1.8	3.2	1.1	E

Appendix 2. Con't

Lake name	Area (ha)	Depth (m)		LCI points				LCI	Secchi depth (m)			Trophic state*
		Max	Mean	DO	TRNS	FSKL	IMPR		Ave	Max	Min	
Washington												
Big	221	7.0	4.3	1	2	0	5	8	2.0	3.8	1.4	E
Liberty	713	9.1	7.0	4	1	(0)	5	10	3.5	5.2	2.7	E
Long	133	6.4	3.7	3	1	0	9	13	2.3	3.4	1.5	E
Loon	457	30.5	14.0	6	0	0	2	8	6.8	7.3	6.4	M
Merrill	197	23.5	11.9	0	0	0	0	0	7.5	10.1	3.0	O
Moses	2,758	10.7	5.6	2	3	0	7	12	0.5	0.6	0.4	VE
Newman	494	9.1	5.8	4	1	0	5	10	2.7	4.0	1.8	E
Sammamish	1,980	32.0	17.7	6	2	0	3	11	3.1	5.5	1.5	M
Silver	668	3.0	1.5	0	3	0	9	12	1.0	2.0	0.8	VE
Steilacoom	128	6.1	3.4	1	2	0	(4)	7	2.0	3.0	1.2	E
Walupt	143	89.9	53.6	2	0	0	0	2	6.8	8.2	5.5	O
Wilderness	28	11.6	6.4	4	1	0	3	8	3.6	5.5	1.5	M
Wisconsin												
Big Green	2,964	69.8	-	2	0	0	2	4	5.4	7.6	2.7	O
Crystal	36	21.0	-	0	0	0	0	0	7.7	9.8	5.8	VO
Delavan	839	17.1	-	6	1	4	4	15	1.6	2.4	0.9	E
Geneva	2,066	41.1	-	2	1	0	2	5	4.6	6.1	2.7	O
Mendota	3,938	25.0	-	6	2	4	5	17	3.1	5.5	1.8	E
Middle	104	12.8	-	4	1	0	2	7	4.4	5.8	3.1	M
Oconomowoc	310	18.9	-	4	1	0	3	8	4.4	7.3	2.7	M
Pewaukee	955	13.7	-	4	2	0	9	15	1.6	2.0	0.9	E
Pine	284	25.9	-	4	1	0	2	7	2.6	4.3	1.7	M
Round	43	20.4	-	4	1	0	2	7	3.9	6.1	2.4	M
Trout	1,566	35.1	-	2	0	0	0	2	4.1	5.2	2.7	O
Winnebago	55,729	6.4	-	3	3	0	7	13	0.7	1.1	0.3	E

Appendix 3. PLOTS OF LCI VERSUS TSI BY STATE

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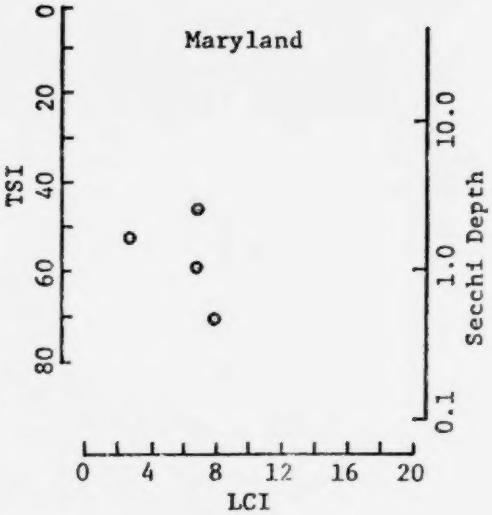
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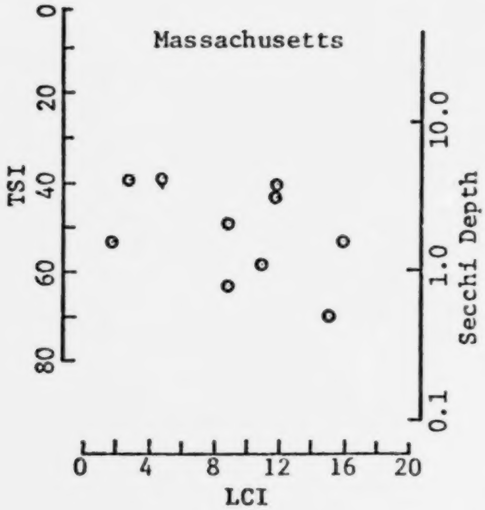
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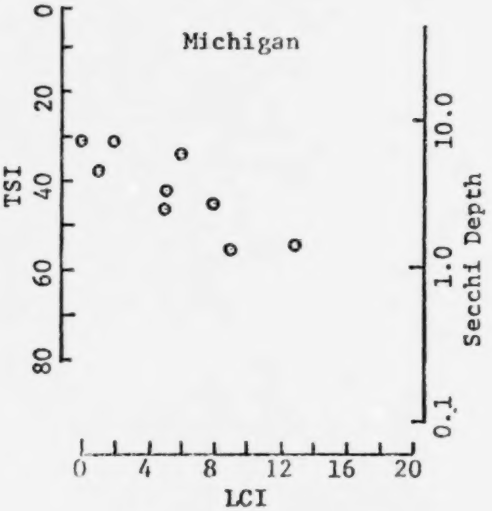
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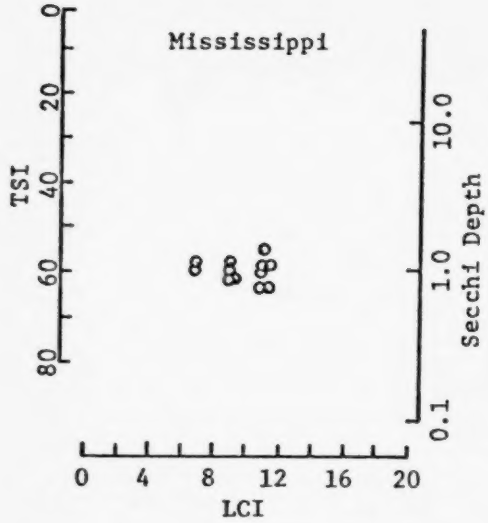
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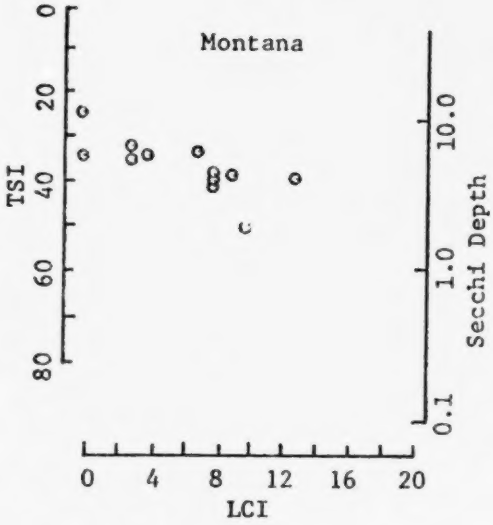
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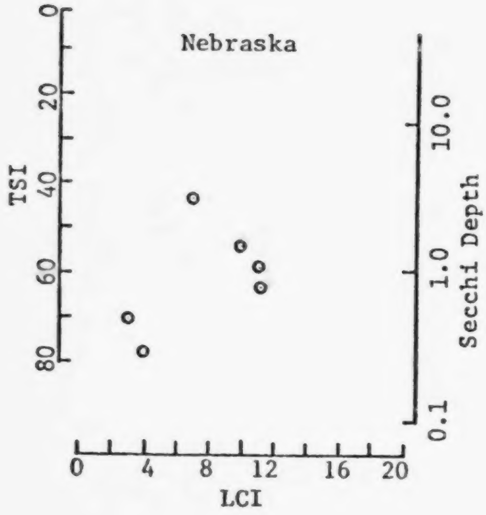
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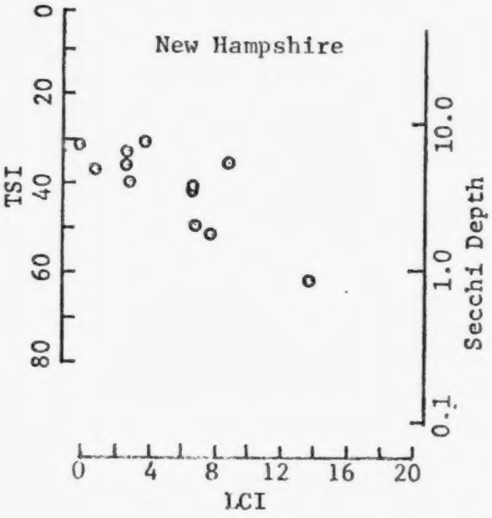
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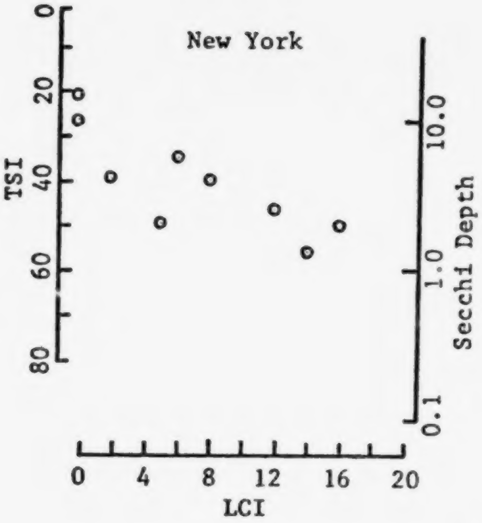
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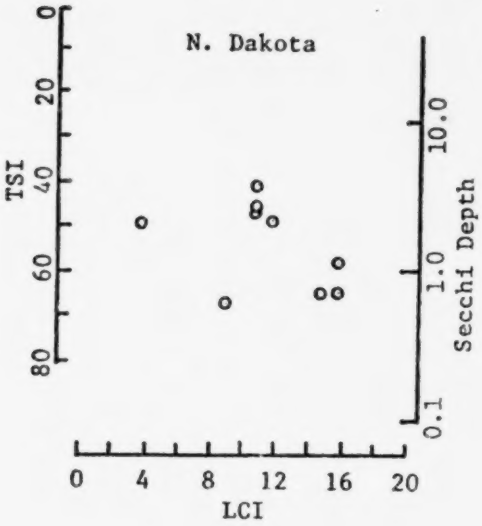
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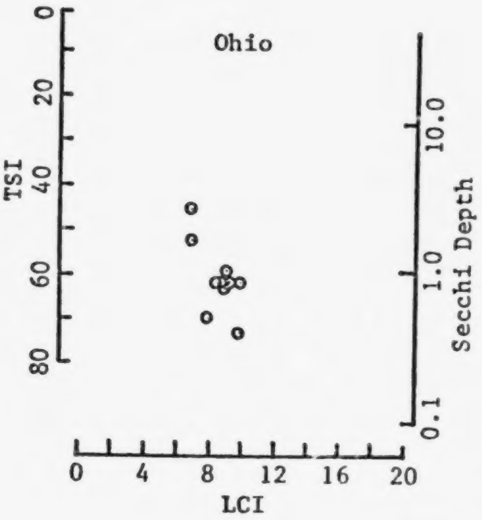
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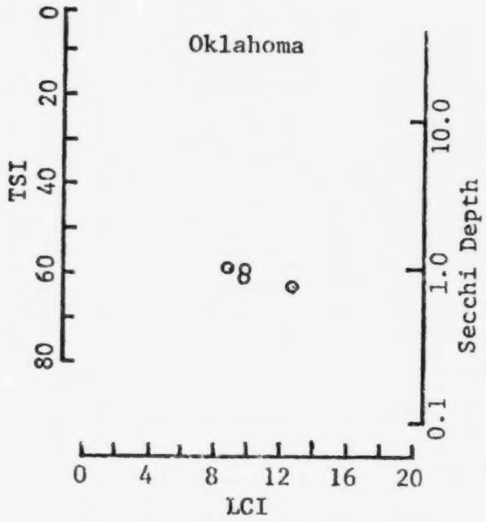
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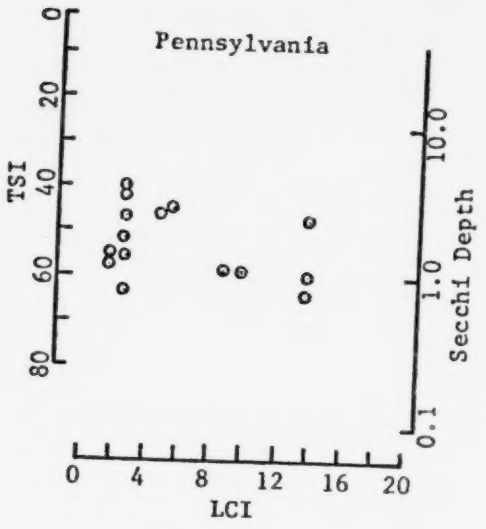
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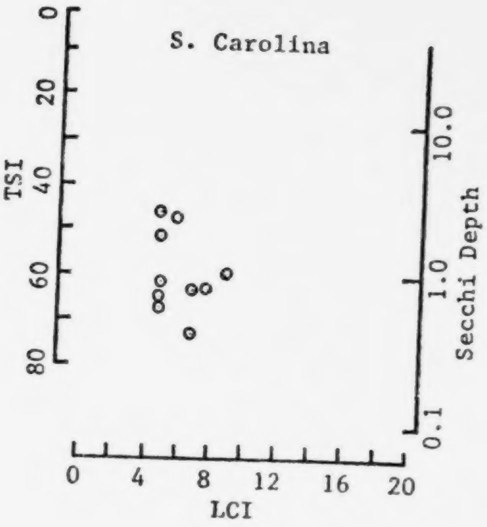
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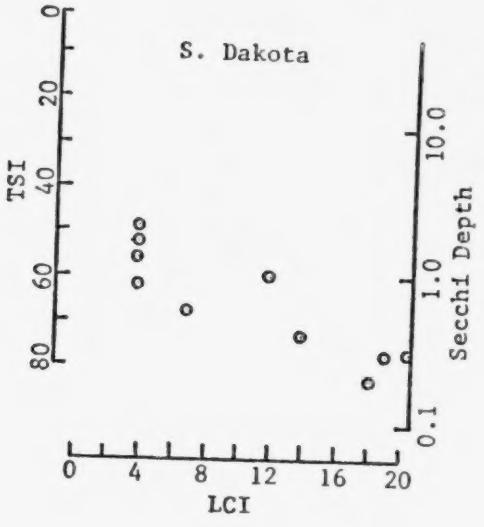
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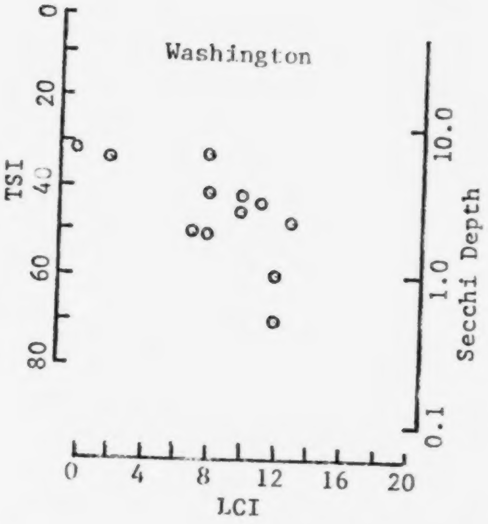
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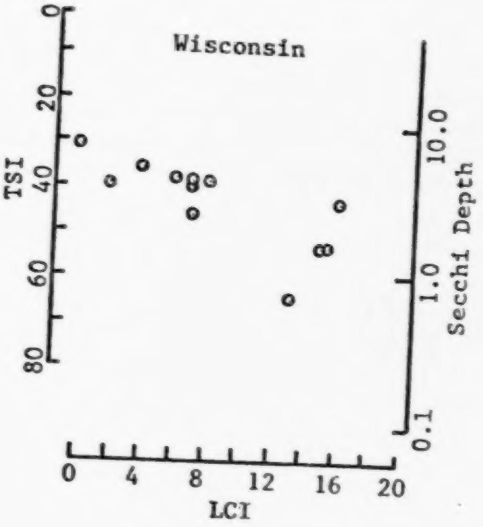

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Secchi Depth
10.0
1.0
0.1
LCI
0
4
8
12
16
20

ACKNOWLEDGMENTS

Data necessary for this report were provided by numerous individuals associated with state agencies and universities throughout the United States. Their cooperation and helpfulness are gratefully acknowledged.

TROPHIC INDICES AND THEIR USE IN TROPHIC CLASSIFICATION OF LAKES AND RESERVOIRS OF NORTH CAROLINA

Charles M. Weiss

Department of Environmental Sciences and Engineering
University of North Carolina at Chapel Hill
Chapel Hill, North Carolina 27514

SUMMARY AND CONCLUSIONS

The trophic state of a lake reservoir is generally measured in terms of the magnitude of the biomass supported by the nutrient flux. To do this directly requires systematic determinations of either cell density or cell volume of the planktonic algae or some other measurement of the organic component produced by cell synthesis that utilizes the available nutrients. It may be expeditious to use indirect determinations of physical, chemical or biological variables which replace to the biomass created by the combination of available nutrients and solar energy. In this study both direct and indirect measures of trophic state were examined to establish the basic relationships and levels of correlation and to use these measures in defining the trophic state of various bodies of water in North Carolina and bordering areas.

Based on the assemblage of 854 observations derived from 69 different bodies of water or subsegments of reservoirs, considerations were given to a wide spectrum of trophic state related indices. These included Secchi depth, chlorophyll a by filtration and solvent extraction, chlorophyll a by Turner photofluorometry, total phosphorus, trophic state indices (Carlson) derived from Secchi depth, chlorophyll a, and total phosphorus, the growth response of reseeded algae into autoclaved or filtered pretreated samples, the Shannon-Weaver and Evenness diversity indices of the specific sample, the number of taxa (species) of algae in the sample, the Pollution Index (the proportional representation in the total population of the rate species associated with high nutrient conditions), several diatom quotients or percentages that have been associated with different trophic states, and the productivity or rate of carbon fixation. All of these indices of trophic condition were related to cell density and cell volume of the sample and their correlation determined over the full range of experienced values.

Within the context of the North Carolina surface waters which were sampled for this study it was apparent that the determination of total phosphorus, conductivity, Pollution Index and Secchi depth were the variables most consistently associated with high correlation levels with the total biomass that was supported by the existing nutrients. Based on the total data pool a range of values for each of these strongly correlated indices was organized in six steps of trophic quality associated with existing water uses. The six level trophic scale was used to describe the trophic condition of 69 lakes.

RECOMMENDATIONS

1. The trophic classification of inland waters can be expedited by the use of water quality parameters which are highly correlated with direct measures of trophic condition and thus serve as trophic state indices. The determinations of Secchi disk transparency, conductivity and total phosphorus are suggested for this purpose. These trophic state indices appear to be particularly effective in describing changes along the longitudinal axis of the river impoundments that are characteristic of the southeastern coastal drainages.
2. To strengthen the validity of the information derived from these quality parameters, determinations should be made at least monthly in the period of intensive public use, e.g. May through September.
3. Monitoring programs of trophic conditions could be substantially enhanced if budgetary considerations could allow for the inclusion of the Pollution Index as a routine analysis.

INTRODUCTION

The trophic state of a lake, or impoundment is a characteristic resulting from the interaction and relationship of many physical, chemical and biological factors, These have been well illustrated in the analog model first suggested by Rawson (1930). They have been redefined by other investigators into a variety of physical, chemical and biological dimensions which may be used in arriving at an integrated statement of the trophic state of an individual body of water (Stewart and Rohlich, 1967), the condition which describes its relative richness with respect to nutrients and organic production. It is not only the specific quality of the existing body of water that is of concern and interest but those factors which when generated by man's cultural activity may cause a change in water quality in the direction of reduced usefulness.

The change in trophic state, generally is a result of an increase in the quantity of algal nutrients, defines the eutrophication of the body of water. Nutrient enrichment of waters frequently results in an array of symptomatic changes such as increased production of algae and other aquatic plants, deterioration of fisheries and other changes in water quality which may be objectionable and impair water use. Although it is recognized that nutrient enrichment is also a natural process, it is accelerated nutrient enhancement that has required development of nutrient classification systems, the trophic state, for lakes and impoundments in order to effect appropriate management procedures.

In an attempt to deal with the complexities of the Rawson model and arrive at a direct method of describing the trophic state, attempts have been made to integrate the several variables in the model to produce a numerical scale or index which could be used for management purposes and to give a more precise meaning to the terms oligotrophic, mesotrophic and eutrophic generally used to scale the intensity of the trophic state. These developments have included the phosphorus loading concepts of Vollenweider and Dillon (1974), and Vollenweider (1975, 1976) which have been instrumental in the development of procedures for predicting quality based upon rate of phosphorus input, lake volume and retention time. Another approach has been the use of multivariate analysis of water quality parameters by Shannon and Brezonik (1972) to classify the lakes of Florida. A classification system developed for South African impoundments by Toerien et al. (1975) draws heavily on much of the European and North American experiences but emphasizes the use of algal growth potential. A statewide effort to classify the trophic characteristics of Wisconsin lakes by Uttormark and Wall (1975) depends on a point system derived from four parameters; dissolved oxygen, transparency, fish kills and use impairment, to derive a lake condition index. The relationships developed by Dillon and Rigler (1975) simplifies the procedures for predicting the nutrient capacity of a lake for the surrounding land development, based on measurements of Secchi disk transparency and chlorophyll a. The development of a comprehensive data analysis system by the New York State Department of Health (Reddy, 1976) seeks to minimize errors inherent in laboratory and field collections in order to facilitate the use of trophic indicator concept, such as primary productivity, total organic carbon, total nitrogen and total phosphorus for the natural waters of New York state. These current efforts have moved from the more simplified examination of specific nutrient elements, (Sawyer, 1947; Wetzel, 1975) and particularly the limiting action of phosphorus on the eutrophication process (Weiss, 1969; Schindler and Lean, 1974).

North Carolina Lake and Reservoir Studies

Recent investigations on individual lakes have included destratification studies to improve water quality (Weiss and Breedlove, 1973), investigations concerned with the impact of electric power generating plants using cooling water from selected lakes and impoundments (Weiss, et al., 1975a) and specific investigations to assess the changing trophic state of a newly impounded body of water to ultimately be used for cooling water purposes (Weiss, et al., 1971, 1972, 1974, and 1975b).

In addition a detailed analysis extending over several years was carried out on the John H. Kerr Reservoir, a major impoundment on the Roanoke River, operated by the Corps of Engineers for flood control and hydropower. This body of water has proved to be of particular significance in characterizing the trophic state of lakes and impoundments of this area due to the circumstance of major nutrient input limited to the inflow into the two arms of the lake each with major differences in retention times. This ultimately converts into different levels of trophic condition. This particular investigation has been part of the North American Project, the OECD-EPA sponsored study organized to examine the Vollenweider concepts on loading. Preliminary reports have considered the loading rates of phosphorus and nitrogen and their relationship to the trophic state of this reservoir (Weiss and Moore, 1975).

PURPOSE AND OBJECTIVES

A majority of the "lakes" of North Carolina have been formed by the impounding of rivers at many suitable dam sites in their flow from the western mountains through the Piedmont to the coastal plain. In many instances these rivers and their impoundments receive substantial quantities of wastewater discharges from major urban areas, It was deemed essential that the effect of these discharges be quantified in terms of their net effect on the trophic condition of the impounded waters in order to establish the effectiveness of pollution abatement efforts currently proscribed by water quality management laws. This baseline datum of water quality for the major inland bodies of water in North Carolina will provide a reference point for future assessment as pollution abatement efforts are carried forward.

The contemporary trophic state of North Carolina waters may not always reflect the magnitude of the nutrient loads that they are currently receiving. The past several decades have seen not only significant increases in average water use with parallel increase in wastewater discharges but also the expansion of urban complexes and extension of sewer lines to serve larger populations. But there are few lakes or impoundments in North Carolina that have reached the level of nutrient enrichment that can be considered undesirable in terms of their current water uses. This report (Weiss and Kuenzler, 1976) is a product of a sampling program integrated with other recent observations to describe current water quality levels to define the trophic state of North Carolina lakes and impoundments. In arriving at definitions of contemporary nutrient levels and associated biological responses the variety of parameters sampled has permitted evaluation of several indicators as to their accuracy and usefulness for water quality monitoring.

The data of this investigation has been derived from a 4-year sampling program of the lakes and impoundments of North Carolina. They are shown for purposes of location and identification on a county map of the state, Figure 1. The map code is identified on Table 1 which also lists the lakes, their particular origin,use, location by county, surface area and mean depth where such information was available. The selection of lakes to provide a cross section of water characteristics was made not only to include impoundments in the several physiographic provinces and major drainage basins but also the few natural lakes mostly identified with the Coastal Plain.

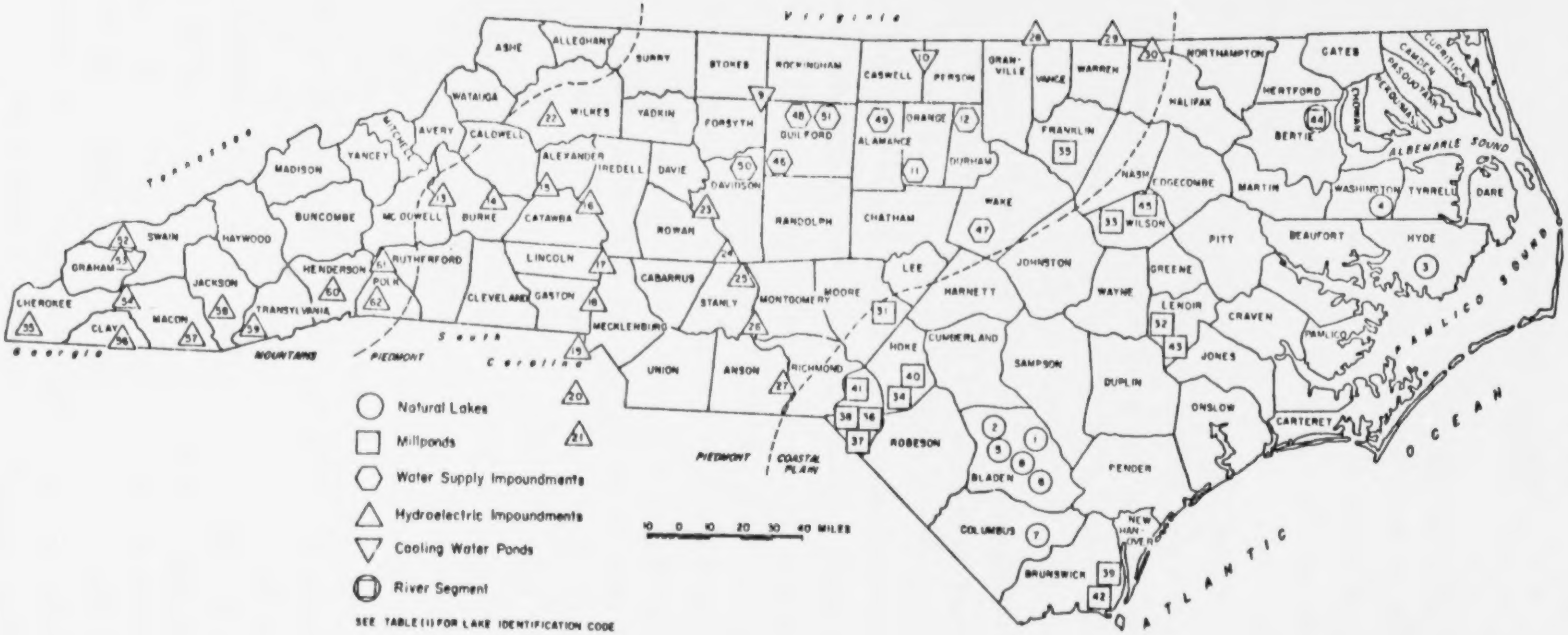
Virginia
Tennessee
Georgia
South Carolina
ATLANTIC OCEAN
ALBEMARLE SOUND
PAMLICO SOUND
MOUNTAINS
PIEDMONT
COASTAL PLAIN
Natural Lakes
Millponds
Water Supply Impoundments
Hydroelectric Impoundments
Cooling Water Ponds
River Segment
SEE TABLE (1) FOR LAKE IDENTIFICATION CODE
10 0 10 20 30 40 MILES
CHEROKEE
GRAHAM
CLAY
SWAIN
MACON
JACKSON
HAYWOOD
TRANSYLVANIA
MADISON
BUNCOMBE
HENDERSON
YANCEY
MITCHELL
AVERY
MC DOWELL
POLK
RUTHERFORD
WATAUGA
ASHE
ALLEGHANY
CALDWELL
BURKE
CLEVELAND
WILKES
ALEXANDER
CATAWBA
LINCOLN
GASTON
SURRY
YADKIN
IREDELL
MECKLENBURG
DAVIE
ROWAN
CABARRUS
UNION
STOKES
FORSYTH
DAVIDSON
STANLY
ANSON
ROCKINGHAM
GUILFORD
RANDOLPH
MONTGOMERY
RICHMOND
CASWELL
ALAMANCE
ORANGE
CHATHAM
MOORE
PERSON
DURHAM
LEE
HOKE
SCOTLAND
GRANVILLE
VANCE
WARREN
FRANKLIN
WAKE
HARNETT
CUMBERLAND
ROBESON
JOHNSTON
SAMPSON
BLADEN
COLUMBUS
BRUNSWICK
NORTHAMPTON
HALIFAX
NASH
EDGECOMBE
WILSON
WAYNE
DUPLIN
PENDER
NEW HANOVER
GREENE
LENOIR
PITT
MARTIN
BERTIE
HERTFORD
GATES
CHOWAN
PERQUIMANS
PASQUOTANK
CAMDEN
CURRITUCK
WASHINGTON
TYRRELL
DARE
BEAUFORT
HYDE
CRAVEN
JONES
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Figure 1. Location and Types of Water Bodies Sampled

Table 1

Surface Waters of North Carolina and Immediate Adjacent Areas Sampled for Trophic State Analysis 1971-1975

	Codes		Surface Area Acres	Mean Depth-Ft.	Location Principal County
Type and Name	Map	Computer			
Natural Lakes					
Black	1	BL	1,420	-	Bladen
Jones	2	JO	225	-	Bladen
Mattamuskeet	3	MA	30,000	-	Hyde
Phelps	4	PH	16,000	-	Washington
Salters	5	SA	315	-	Bladen
Singletary	6	SL	570	-	Bladen
Waccamaw	7	WA	8,940	4.9	Columbus
White	8	WH	1,070	-	Bladen
Impoundments					
Cooling Water					
Belews	9	BC	3,700	50.3	Stokes, Rockingham
Hyco	10	HY	3,750	20.5	Person
Water Supply					
University	11	UN	200	9.4	Orange
Michie	12	MC	507	25.6	Durham
High Point	46	HP	300	13.5	Guilford
Wheeler	47	WE	540	11.4	Wake
Brandt	48	BR	800	8.4	Guilford
Burlington	49	BU	755	13.0	Alamance
Lexington-Thomasville	50	LT	785	8.3	Davidson
Townsend	51	TO	1,600	12.4	Guilford
Hydroelectric and Flood Control					
Roanoke River					
John H. Kerr	28	KR	48,900 (elev. 300)	33.7	Mecklenberg, Va. Vance, N.C.
Gaston	29	GA	22,000	18.8	Warren
Roanoke Rapids	30	RR	4,900	15.8	Halifax
Yadkin River					
W. Kerr Scott	22	KS	3,980	38.4	Wilkes
High Rock	23	HR	15,180	16.3	Davidson, Rowan
Tuckerton	24	TU	2,530	17.0	Davidson, Rowan
Badin	25	BA	5,970	23.8	Montgomery, Stanly
Tillery	26	TL	5,000	33.6	Montgomery, Stanly
Blewett Falls	27	BW	2,500	36.0	Richmond, Anson

Table 1 (continued)

Type and Name	Codes		Surface Area Acres	Mean Depth-Ft.	Location Principal County
	Map	Computer			
Catawba River					
James	13	JA	6,510	46.1	McDowell, Burke
Rhodhiss	14	RH	3,515	20.8	Caldwell, Burke
Hickory	15	HK	4,110	31.0	Alexander, Catawba
Lookout Shoals	16	LS	1,270	24.5	Iredell, Catawba
Norman	17	NR	32,510	33.6	Catawba, Iredell, Lincoln, Mecklenberg
Mt. Island	18	MT	3,235	17.7	Mecklenberg, Gaston
Wylie (N.C.-S.C.)	19	WY	12,455	22.5	Mecklenberg, Gaston,N.C. York, S.C.
Fishing Creek (S.C.)	20	FC	3,370	17.1	Chester, Lancaster,S.C.
Wateree (S.C.)	21	WT	13,710	22.6	Fairfield, Kershaw,S.C.
Broad River					
Lure	61	LU	1,500	-	Rutherford
Green River					
Adger	62	AD	440	26.7	Polk
Summit	60	SM	325	40.7	Henderson
Toxaway River					
Toxaway	59	TX	650	-	Transylvania
Hiwassee River					
Chatuge	56	CT	7,150	34.5	Clay
Hiwassee	55	HW	6,280	69.7	Cherokee
Nantahala River					
Nantahala	54	NA	1,605	86.4	Clay, Macon
Cheoah River					
Santeetlah	53	SN	2,860	55.2	Graham
Little Tennessee River					
Fontana	52	FO	10,670	135.4	Graham, Swaim
Highland	57	HL	400 est.		Macon
Tuckaseigee River					
Thorpe	58	TH	1,462	48.4	Jackson
River Segment					
Chowan (U.S. 13 to Albemarle Sound)	44	CH	-	-	Hertford, Gates, Chowan, Bertie

Table 1 (continued)

Type and Name	Codes		Surface Area Acres	Mean Depth-Ft.	Location Principal County
	Map	Computer			
Old Mill Ponds (year constructed)					
Crystal (1885)	31	CL	100	-	Moore
Davies (1850)	32	DM	60	-	Lenoir
Finches (1875)	33	FH	20	-	Wilson
Hodgins (1871)	34	HO	100	-	Hoke
Jackson (1885)	35	JK	75	-	Franklin
Johns (1840)	36	JH	125	-	Scotland
Jones (1810)	37	JP	75	-	Scotland
Lytches (1870)	38	LY	325	-	Scotland
McKensie (1860)	39	MK	50	-	Brunswick
McNeils (1870)	40	MN	100	-	Hoke
Monroe (1825)	41	MO	70	-	Scotland
Orton (1810)	42	OR	500	-	Brunswick
Tull (1875)	43	TM	180	-	Lenoir
Silver (1785)	45	SI	75	-	Wilson

PROCEDURES

Trophic and Quality Parameters

In the definition of trophic state the task becomes one of quantifying the magnitude of the biomass supported by the nutrient flux. This measurement may be made at the primary level either by enumeration of the cell density of the planktonic algae and/or cell volume. Since this determination is influenced by the sampling procedures and quantifying techniques it does not necessarily describe the net integrated effect of primary productivity. Other measures have also been used to arrive at an assessment of trophic state such as rate of carbon fixation (primary productivity); the major components of the nutrient flux, nitrogen, phosphorus and carbon; or the relative transparency of the water (Secchi disk depth) under the assumption that the degree of turbidity is a direct indication of the particulate material of biological origin obscuring the passage of light.

The following definitions or descriptions are of the measured or calculated water quality parameters used in the assessment of various trophic indices as to their validity and utility. Each water sample was considered a microcosm, constituting the physical and chemical environment of a specific microflora (planktonic algae). Ultimately a set of 854 observations from all bodies of water sampled were treated as a data pool for the following comparisons.

Physical and Chemical

Temp. °C: The temperature of the water sample measured in degrees Celsius was usually obtained with a thermister probe. The value reported is either representative of the average value of the epilimnion at the time of sampling or the specific temperature at the depth that the sample was taken for algal analysis.

Secchi-Ft.: The Secchi depth at the time of sampling, measured in feet. This was the calibration used for most of the field of work of this investigation. The Secchi depth was generally estimated to the nearest half foot.

Secchi-M: Secchi depth in meters as calculated from the field measurement or in the later stages of the field work measured in the field to the nearest 0.1 M.

NH_3-N: Ammonia nitrogen, determined by the automated phenolate method on a

Technicon Autoanalyzer (U. S. EPA, 1974). The water sample was pretreated by filtering through a washed Millipore HA filter.

NO_2NO_3-N: Nitrite and nitrate nitrogen, determined by reduction with hydrazine sulphate (U. S. EPA, 1974). The procedure was carried out on a sample pretreated by filtration through a washed Millipore HA filter. The analysis was made on a Technicon Autoanalyzer with the color being measured at 520 mm.

Kjel-N: Kjeldahl nitrogen, determined on a Technicon Autoanalyzer using the automated phenolate method on an unfiltered sample. The sample was digested in a continuous digestor with sulfuric acid containing potassium sulfate and mercuric sulfate as a catalyst.

Inorg-N: Inorganic nitrogen, representing the sum of NH_3-N and NO_2NO_3-N in the sample.

Org-N: Organic nitrogen, representing the difference between Kjel-N and NH_3-N and thus defining the actual nitrogen, found in cellular materials, which are released by the digestion process.

Total-N: The sum of NO_2NO_3-N and Kjel-N.

PO_4-P: Orthophosphate phosphorus, determined on a sample filtered through a washed Millipore HA filter using the automated stannous chloride method (U. S. EPA, 1974) in a Technicon Autoanalyzer.

Total Sol-P: Total soluble phosphorus or dissolved phosphorus as determined in a sample after filtration through a washed Millipore HA filter. The dissolved or soluble fraction is digested with potassium persulfate and sulfuric acid followed by the automated stannous chloride method for determination of the reactive phosphorus.

Particulate-P: The phosphorus component associated with particulate materials and determined by difference between the Total-P and Total Sol-P.

Total-P: The total phosphorus component determined on an unfiltered water sample manually digested with potassium persulfate and sulfuric acid to convert various forms of phosphorus to the orthophosphate with final determination as PO_4-P using the automated stannous chloride method.

TN/TP: The ratio of total nitrogen to total phosphorus.

Inorg-N/Sol-P: The ratio of inorganic nitrogen to total soluble phosphorus.

Alk: Total alkalinity as $mgCaCO_3$ and determined on a 100 ml water sample titrated with .02N HCl. The equivalence point of pH 5.1 is determined potentiometrically.

Cond µmhos: Conductivity in micromhos per cm. at 25°C determined either on a water sample returned to the laboratory utilizing a Lab-Line Electro MHO meter or in the field with a YSI Model 33 field temperature/salinity/conductivity meter.

Turbidity: Determined on Hach Model 2100 turbidimeter calibrated against a Formazin standard and reported as Jackson turbidity units (JTU).

Color: Determined on a raw water sample by comparison with potassium chloroplatinate standards.

Biological

Chlor a: Chlorophyll a, determined on a water sample filtered onto a Gelman glass fiber filter and acetone extracted using the techniques of Strickland and Parsons (1972) and the pheophytin correction equations of Lorenzen (1967). Absorbance of the acetone extract was determined at wavelengths of 665 mμ and 700 mμ (turbidity correction) using a Beckman DB spectrophotometer and 4 cm absorption cells.

Chlor a-Turner Units: Chlorophyll a determined by its fluorescence on excitation with ultraviolet light using a Turner model 110 fluorometer equipped with a Hamamatsu R136 photomultiplier, a high sensitivity sample holder, Corning 5-60 primary filter and 2-64 secondary filter. Samples were read directly on the fluorometer and all results converted to the instruments 10x scale. The Turner chlorophyll values are significantly correlated with chlorophyll a as determined by standard procedures. A conversion of Turner Units to chlorophyll a mg/m^3 can be approximated by multiplying by a factor of .38 in the range of 0-100 Turner Units and .46 in the range of 100-250 Turner Units.

Prod $mgCm^3/hr$: The productivity of the water sample, reported in milligrams carbon fixed per $meter^3$ per hour, was determined on raw samples brought back to the laboratory, stored overnight in the dark at room temperature and incubated in light/dark bottles under 400 ft. candles of fluorescent "daylight lamps" at 24°C. Changes in dissolved oxygen over a six hour incubation period were determined by Winkler titration and converted to carbon equivalence using a photosynthetic quotient of 1.2. The samples incubated for productivity determination were aliquots of the same water returned for algal cell density determinations.

Cells no./ml: All cell density determinations were made on live samples, but if necessary held overnight in a refrigerator. Measured portions (normally 10 ml) from a well shaken sample were placed on a tapered centrifuge tube and centrifuged at maximum speed in a clinical centrifuge for 15-20 minutes. The liquid above each concentrated sample was carefully drawn off by pipette until about .05 ml were left. The concentrated material was resuspended and thoroughly mixed in the remaining water. These drops were transferred by pipette to a clean microscope slide filling the area under a 22 x 22 mm cover glass. The cover glass was sealed with a paraffin-petroleum jelly mixture to prevent rapid drying. The live preparation was examined under a Zeiss GFL compound microscope to determine the uniformity of cell distribution and absence of air bubbles. The preparation was examined at 500 x to identify and enumerate phytoplankton in selected transects of known width and length using an oil immersion lens at 1250 x for careful identification and measurement of smaller species. In the case of colonies and filaments the entire units were counted making note of the average number of cells per unit. The number of cells in units/ml in the original sample was calculated from a known area of cover glass, the area of the transects counted and the original volume of the sample concentrated under the cover glass.

Biovol: A standard cell volume was determined for each species, calculated by water displacement of plasticene clay scale models constructed from observations and average measurements of each taxa. Considerations were given to the average number of cells per unit of colonial and filamentous forms and the large central vacuoles of diatoms. The unit volume, mm^3/m^3 is equivalent to mg/m^3, $10^3\mu^3/ml$ or $10^{-3}\mu l/l$, other units commonly used for reporting biomass and biovolume.

A detailed description of the phytoplankton population of each of the lakes on each of the sampling dates was not considered essential for this report in defining the trophic state. A comprehensive analysis of population characteristics and associated environmental factors is to be reported elsewhere (Campbell and Weiss, in preparation).

Diversity Indices: The quantitative definitions of population size, such as cell density and biovolume and proportional representation of specific groups or classes were used to compute other indices of trophic status. These provide additional scales for comparative assessment of the trophic level reached by a specific body of water. Such measures of trophic state include the Shannon-Weaver (Shannon and Weaver, 1949) and Evenness (Patten, 1962) diversity indices and the Pollution Index. The Shannon-Weaver (Shan-Wea) was chosen because of its independence of sample size and sensitivity to change in evenness of distribution for a small number of species and insensitivity to rarer missing species. It is assumed that values approaching and surpassing 3.0 are considered indicative of highly diverse systems and these are generally associated with waters of high quality.

The Evenness index or evenness of distribution of individuals among species has a range approaching zero for an extremely skewed distribution to 1.0 for a perfectly even distribution e.g. one with the same number of individuals in each species. Values approaching 1.0 are generally associated with water of high quality.

The Pollution Index, modified from Palmer (1969) to account for changes in overall cell density, depends on a scaling of eighty pollution tolerant species with values assigned by Palmer. The density of their number in the sample multiplied by the number of units/ml for that species and the accumulated total of the sample divided by the total number of taxa found provides a numerical index ranging from zero to over 1000 (Weiss et al., 1974). This index has proved to be unusually valuable and sensitive to changes in quality, the presence of the pollution tolerant species being a key element in nutrient rich systems.

Phytoplankton Quotients

With the facility of computers to handle large data banks and rapidly calculate the above diversity indices for each sample, it was also possible to utilize the raw species count and examine other biological indices that have been used to describe changes in trophic state, Nygaard (1953), Rawson (1956), Brook (1965), Stockner and Benson (1967) and Stockner (1972). These relationships were applied to the diatom composition of the contemporary planktonic populations of the 854 samples of this study. Several of these relationships have been computed. They are described in Table 2 and are referred to in the

Table 2

Biological Indices
Phytoplankton Quotients

Code	Class or Group Relationship	Trophic State
BI-A[1]	$\frac{\text{Species - Chlorococcales}}{\text{Species - Desmidiaceae}}$	<1 oligotrophy >1 eutrophy
BI-B[2]	$\frac{\text{Species}}{}$	0.0-0.3 dystrophy
	$\frac{\text{Cyanophyceae + Chlorococcales + Centrales + Eugleniaceae}}{\text{Desmidiaceae}}$	<1 oligotrophy 1-2.5 mesotrophy 2.5-5.0 eutrophy 5.0-2.0 hypereutrophy
BI-C[2]	$\frac{\text{Species - Centrales}}{\text{Species - Pennales}}$	0-0.2 oligotrophy 0.2-3.0 eutrophy
BI-D[2]	$\frac{\text{Centrales}}{\text{Centrales + Araphidineae}}$ as % C + A (Density)	>50% eutrophy 32-50% mesotrophy <32% oligotrophy
BI-E[3]	$\frac{\text{Centrales}}{\text{Centrales + Araphidineae}}$ as % C + A (Volume)	

[1] Rawson (1956)
[2] Nygaard (1955)
[3] Modified from Stockner (1971)

text and other tables by the codes BI-A, BI-B, BI-C, BI-D and BI-E.

Contemporary with the period of water sampling covered in this report parallel studies, as part of a Federal, University, Industry effort to develop an algal assay for limiting nutrients, was part of the ongoing research effort of this laboratory (Weiss and Helms, 1971: Weiss, 1976). Many of the samples taken for assay have also been incorporated in the 854 observations of this report. The weight of the biomass grown with a reseeded species under control light and temperature conditions, without nutrient enhancement, provided an indication of the growth potential of the body of the water. In the instance where the sample was pretreated by autoclaving the total potential for growth was indicated. In the second case of pretreatment, filtration, the potential for growth reflects the immediate available nutrients. This control growth has been used as another trophic indicator, reflecting the current net nutrient level of a body of water as well as the potential for algal growth. The pretreatment methods are identified as aut. wgt. and filt. wgt., e.g. weight of biomass grown in the autoclaved pretreated sample and weight of biomass grown in the filtered pretreated sample.

Trophic State-Indices (Carlson)

Due to the variation in interpretation of the meaning of the terms associated with the quality parameters, Carlson (1975) proposed a trophic state index scale (TSI) based on Secchi-disk transparency (meters), chlorophyll a (mg/m^3) and total phosphorus (mg/m^3). He established a scale ranging from 0 to 100 based upon lowest and highest reported values in the literature. The major divisions are grouped into units of 10's (10, 20, 30, etc.). These divisions correspond approximately to existing concepts of trophic categories. Carlson's range of values for TSI are shown in Table 3. In each instance 0 represents the most oligotrophic state and 100 the most eutrophic. Utilizing the data from the North Carolina lakes, the TSI has been computed for each and included in the trophic index analysis. These three indices are referred to as the SD-TSI, CH-TSI and TP-TSI. In addition to the three computed indices the three original parameters have also been utilized in scaling the quality of the sampled waters.

Table 3

Trophic State Index (TSI) and Associated Parameters[1]

TSI	Secchi Disk Depth-Meters	Surface Total Phosphorus (mg/m^3)	Surface Chlorophyll (mg/m^3)
0	64	1	.04
10	32	2	.12
20	16	4	.34
30	8	8	.94
40	4	16	2.6
50	2	32	6.4
60	1	65	20
70	0.5	130	56
80	0.25	260	154
90	0.12	519	427
100	0.062	1032	1183

[1] From Carlson (1975)

RESULTS AND DISCUSSIONS

Data Analysis

The data of this report, generated from four years of sampling of lakes and impoundments located in the representative geographic provinces of the State of North Carolina provided an opportunity to examine the usefulness of various trophic state indicators for assessment of trophic condition. In all 854 individual observations were sufficiently complete both in terms of observed or measured data as well as other parameters calculated from the primary determination to be used in a data pool. This information has been examined by various sorting and statistical techniques so that the associations of dependent and independent variables could be examined over the full range of values.

Many of the impounded basins on the North Carolina river systems receive point source discharges from municipalities, either by direct discharge to the reservoir or into the inflowing river or stream. In some instances the river and its nutrient load creates sharp quality gradients which permits the data from large impoundments to be examined in subsegments along the longitudinal axis, essentially testing in situ the mechanisms of quality change and the associated trophic indicators or scales.

Each of the 854 water samples have been treated as an independent entity in order to examine the physical, chemical and biological environment of the specific microcosms. By computer sorting procedures each of the individual water quality parameters or trophic indicators were rank ordered and listed with associated variables. In turn the rank orders were divided into a series of subclasses or subsets of data. These subsets covered value ranges of some logical interval, such as a doubling sequence or were divided at points in the rank order where sharp discontinuities were indicated. The mean values of all other parameters or variables that occurred within the subclass were then calculated. The mean values of each subclass of the independent variable was then compared to the mean values of all other parameters measured or calculated under similar associated conditions. From such analyses of the relationships of the various trophic indices to those recognized dimensions of trophic state the indices which appear to serve best to describe a trophic scale have been highlighted.

Secchi Depth

The classic procedure for determining water transparency has been to use the Secchi disk for measuring the depth to which it can be viewed. This depth is inversely proportional to the suspended particulate material that is primarily of biological origin. The deeper the disk is viewed, the clearer the water, thus smaller quantities of particulates of biological origin and consequently the general assumption of water of higher trophic state. Over a range of Secchi depth values from 0.1 to more than 4 meters, in seven subsets, the values of the other trophic indices are all negatively correlated decreasing as transparency increased (Table 4). However, a few are negatively correlated at very significant levels and thus would appear to have a stronger direct relationship to the Secchi depth than others with poor correlation or at non-significant levels. For example strong correlation is seen for chlorophyll a, cell density, cell volume, the Shannon-Weaver and Evenness indices of diversity. However, both of the latter appear to have a sharp divergency from the regression slope in the deepest range of Secchi values. The pollution index, taxa and several of the biological indices particularly BI-A, BI-B, BI-C and BI-E are also significantly correlated (negative) with Secchi depth. The biological indices do not necessarily agree in scale as to where one trophic state phases into another but of the five, the BI-E scale would appear to come closest to the definition of oligotrophy at the deepest Secchi disk readings. Another anomaly is noted for BI-B. Across the entire range of values, even through changing systematically with increase of Secchi depth, it still indicates by the magnitude of the index, to be in a state of hypereutrophy. Note should be made of the very good correlation between Secchi depth and the scale of the Pollution Index which decreased systematically as the Secchi depth increased.

The best of these correlations and others, will be compared in a cross relationship to establish the most consistent of the indices and how they might be used to define trophic state.

Chlorophyll a

By the standard determination for chlorophyll, filtration and acetone extraction followed by absorption photometry, a range of values from as low as 0.8 to over 160 mg/m^3 have been defined in eight subsets. In addition to

Table 4

Mean Values of Trophic State Indices
Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

Secchi-Depth-Meters

Range of Values	0.1-0.49	0.5-0.98	1.0-1.49	1.5-1.99	2.0-2.99	3.0-3.99	>4.0	Corr. Coef. r(xy)**
N*	103	309	186	134	82	23	5	
Secchi-M (x)	0.31	0.75	1.2	1.6	2.3	3.3	4.7	-
Chlor a mg/m^3	31(30)	24(72)	14(39)	10(40)	3.7(20)	3.2(7)	2.5	-.85
TP mg/m^3	117	62	30	21	15	15	13	-.72
SD-TSI	76.4	63.7	56.8	52.1	47.3	42.6	37.2	-.92
CH-TSI	57.6	59.2	54.4	51.1	41.8	41.8	39.8	-.91
TP-TSI	66.5	56.0	45.2	41.9	37.7	37.2	35.8	-.81
Color Pt Units	77(48)	49(102)	24(52)	12(39)	13.6(17)	9.7(8)	9.8	-.74
Turb. JTU	41(58)	14(149)	9(83)	7(79)	4.5(67)	3.6	2.0	-.69
Aut. Wgt.	14.0(34)	6.1(96)	2.5(64)	3.4(38)	1.8(18)	0.5(4)	-	-.80
Filt. Wgt.	5.5(34)	2.5(96)	0.9(64)	1.3(38)	0.7(18)	0.4(4)	-	-.78
Cell Den.no./ml	5657	6691	4549	3439	2154	1093	516	-.93
Biovol. mm^3/m^3	2875	2748	2144	1875	1274	857	1461	-.81
Shan-Weaver	3.896	3.597	3.701	3.634	3.294	2.997	3.567	-.98
Evenness	.738	0.659	0.664	0.651	0.641	0.623	0.717	-.08
Pollution Index	113	145	107	77	39	49	6	-.91
Taxa, no. sp.	39	44	46	45	33	25	27	-.82
BI-A	7.9	8.1	7.4	6.1	5.1	4.8	3.5	-.962
BI-B	15.2	14.3	12.6	10.3	8.0	7.0	5.8	-.95
BI-C	1.3	1.5	1.4	1.4	1.3	1.4	0.7	-.75
BI-D	81.8	84.3	78.5	72.6	70.9	77.7	40.0	-.84
BI-E	76.1	77.2	69.4	63.4	54.8	62.8	31.9	-.92

*If N deviates from values shown by more than 10% then actual N is in parenthesis.
**5% level of significance >.666
1% level of significance >.798.

describing the relationships with the other trophic state indicators, (Table 5) the data analysis has also been extended to include relationship of chlorophyll a to other physical and chemical and biological dimensions that were determined on each of the water samples (Table 6).

The relationship of chlorophyll a to other trophic indicators is obviously strongest with those parameters either directly related, other cellular measurements, or chemical constituents which have been shown to be essential in the growth of algal cells such as phosphorus. The strongest correlations are with total phosphorus, the trophic indices of Carlson computed from Secchi depth, chlorophyll and total phosphorus, the relationships to cell density and biovolume, Pollution Index and the biological indices A, B, D and E.

When the range of chlorophyll values are examined in relationship to other parameters of the aquatic environment, the strong negative correlation with temperature is perhaps unique. It would suggest that the optimum for growth was at somewhat lower temperatures than might be expected. The unusually strong correlation of kjeldahl-nitrogen and organic nitrogen would indicate that these determinations described materials directly associated with the source of chlorophyll. The strong correlations with the phosphorus constituents and particularly particulate phosphorus argue for a similar source relationship. The strong negative correlations with the ratios total nitrogen/total phosphorus and inorganic nitrogen/soluble phosphorus, identify the proportions needed for maximum growth. The strikingly high correlation with conductivity suggests the use of this determination for monitoring purposes.

Chlorophyll a-Turner Units

Since the determination of chlorophyll a by the standard extraction procedure is time consuming and requires attention to detail that may not be feasible on all occasions or in all laboratories, chlorophyll by direct photofluorometry was determined on many samples. The range of values for this determination and relationships to the trophic state indices as well as the other physical, chemical and biological parameters, are noted in Tables 7 and 8.

The highlights of these comparisons are that the photofluorometric measurements also produced many relationships with high correlations, although perhaps not quite as good as those of the extraction procedure. There was indicated at the lower subclasses of the range of values of associated parameters little change in proportion to the change in size of the mean Turner value, an

Table 5

Mean Values of Trophic State Indices
Derived from Lake Samples Collected for Trophic Analysis
Arranged Within Value Range of Given Index

Chlorophyll a mg/m^3

Range of Values	0.8-2.0	2.1-5.0	5.1-10.0	10.1-20.0	20.1-40.0	40.1-80.0	80.1-160	>160.1	Corr. Coef. r(xy)**
N*	19	42	35	51	42	15	8	1	
Secchi-M	2.1	1.7	1.3	1.2	0.9	0.6	.4	.46	-.72
Chlor a(x)	1.6	3.4	7.5	15	27	51	96	204	-
Total-P	37	47	57	33	63	100	280	900	.957
SD-TSI	52.6	57.4	57.3	58.7	61.9	67.7	74.5	71***	.975
CH-TSI	35.2	42.8	50.4	56.9	62.9	69.1	75.1	82***	.91
TP-TSI	43.5	49.5	48.4	48.3	55.7	64.0	80.7	99***	.989
Color	2(15)	4(34)	4(31)	44	27	48	30	14***	-.14
Turbidity	11	7	2	9.4	4	17	29	27***	.88
Aut. Wgt.	0.1(1)	5.3(2)	0.3(5)	-	1.5(1)	-	-	-	-
Filt. Wgt.	0.1(1)	0.1(2)	0.2(5)	-	0.1(1)	-	-	-	-
Cell Density	919	1931	4532	12149	15981	19937	43845	58965	.965
Biovolume	775	1356	2300	4057	5407	7650	13065	76008	.950
Shan-Wea	3.443	3.421	3.788	3.459	4.133	4.300	4.134	4.495***	.74
Evenness	0.694	0.656	0.673	0.609	0.689	.705	0.687	.698***	.35
Pollution Index	12	30	86	122	274	591	1481	4132***	.99
Taxa	30	35	49	51	64	68	66	86***	.76
BI-A	3.9	5.3	7.0	7.9	10.6	12.8	14.9	10.7***	.90
BI-B	6.5	9.4	12.9	14.0	17.7	20.5	22.5	19.7***	.88
BI-C	0.8	1.0	1.3	1.2	1.5	1.1	1.3	0.9***	.38
BI-D	60.2	64.5	62.7	59.2	79.4	88.4	96.7	99.9***	.93
BI-E	45.7	56.2	57.6	44.5	69.0	77.4	90.0	99.6***	.91

*If N deviates from values shown by more than 10% then actual N is in parenthesis.
**5% level of significance >.707
1% level of significance >.834.
***Because of smallness of N these values not used in calculating corr. coef.

Table 6

Mean Values of Physical, Chemical and Biological Parameters of Lake Samples Collected for Trophic Analysis Within Value Range of Indicated Parameter

Chlorophyll a mg/m^3

Range of Values	0.8-2.0	2.1-5.0	5.1-10.0	10.1-20.0	20.1-40.0	40.1-80.0	80.1-160	>160	Corr. Coef. r(xy **
N*	19	42	35	51	42	15	8	1	
Temp °C	22.3	20.7	22.1	22.8	21.3	17.9	13.0	27***	-.95
Secchi-Ft.	7.0	5.5	4.4	3.9	3.0	2.0	1.2	1.5***	-.87
Secchi-M	2.13	1.68	1.33	1.18	0.88	0.59	0.4	.46	-.72
NH_3-N mg/m^3	63	53	55	47	66	76	467	100	.36
NO_2NO_3-N mg/m^3	86	113	74	71	77	62	98	60	-.39
Kjel-N mg/m^3	214	230	265	288	377	532	1175	1400	.955
Inorg-N mg/m^3	149	166	129	119	143	138	565	160	.30
Org-N mg/m^3	151	177	210	240	311	456	708	1300	1.00
Total-N mg/m^3	299	343	339	356	454	594	1272	1460	.95
PO_4-P mg/m^3	5	7	23	9	13	20	95	115	.93
Total Sol-P mg/m^3	10	17	31	12	22	34	158	600	.963
Sol Org-P mg/m^3	5	10	8.2	3.5	8.7	14	63	485	.93
Particulate-P mg/m^3	27	31	26	21	41	66	122	300	.990
Total-P mg/m^3	37	47	57	33	63	11	280	900	.957
TN/TP	17.6	12.1	14.6	15.3	14.4	11.3	4.6	1.6	-.92
Inorg N/Sol P	18.5	11.7	11.1	15.2	15.4	9.3	4.7	.27	-.89
Alk mg/l	10	12	19	20	23	25	29	31	.81
Cond µmhos	56(15)	56	106	112	119	174	308	612	.996
Cell Den no/ml	919	1931	4532	12149	15981	19937	43,845	58,965	.965
Biovol mm^3/m^3	775	1356	2300	4057	5407	7650	13,065	76,008	.950
Ln Cell Den	6.5681	7.0227	8.0377	8.8359	9.2843	9.694	10.4082	10.9847	.82
Ln Biovol	6.3677	6.7345	7.507	7.9639	8.3003	8.753	9.2905	11.2386	.94
Chlor a-Turner Units	15	21	35	39	67	102	164	182	.92
Prod mg C/m^3/hr	10(13)	15(31)	26(32)	44	80	141	239	309	.958

*If N deviates from values shown by more than 10% then actual N is in parenthesis.

**5% level of significance >.666, 1% level of significance >.798.

***Not used in calculating corr. coef.

Table 7

Mean Values of Trophic State Indices Derived from Lake Samples Collected for Trophic Analysis Arranged Within Value Range of Given Index

Chlorophyll a Turner Units

Range of Values	7-14	15-29	30-44	45-59	60-89	90-119	120-179	180-239	>240	Corr. Coef. r(xy)**
N*	135	314	138	53	44	22	18	3	2	
Secchi-M	1.5	1.2	1.1	1.0	0.8	0.7	0.5	0.5	0.4	-.90
Chlor a	4.9(22)	6.3(64)	13.9(52)	20.2(22)	26.5(21)	44(18)	67(9)	144	129	.94
Total-P	35	42	38	52	94	114	173	460	297	.85
SD-TSI	57.1	59.6	59.9	60.0	64.5	65.9	69.3	68.0	74.5	.967
CH-TSI	41.4(22)	46.5(64)	55.2(52)	59.6(22)	61.0(21)	66.7(18)	70.8(9)	78.0(2)	80.0	.93
TP-TSI	47.0	48.4	50.0	52.8	61.2	66.4	72.7	85.3	82.0	.95
Color	24(32)	34(99)	41(70)	17(23)	101(23)	36(17)	67(9)	22	17	-.14
Turbidity	8	18(157)	13(93)	13(30)	15(29)	17(20)	20(15)	23	22	.82
Aut. Wgt.	5.5(28)	4.5(92)	4.7(54)	7.3(18)	4.7(12)	9.1(4)	12.5(6)	-	6.0(1)	.36
Filt.	3.0(28)	1.8(92)	1.2(54)	2.9(18)	2.6(12)	1.2(4)	6.9(6)	-	2.1(1)	.20
Cell Density	1206	2560	6732	9155	9394	17194	25849	60203	33680	.82
Biovolume	1028	1211	2558	3862	3826	7713	8865	35595	19197	.79
Shan-Wea	3.226	3.613	3.644	4.020	4.040	4.110	4.068	4.170	3.798	.49
Evenness	0.653	0.676	0.639	0.679	0.677	0.696	0.681	0.663	0.637	-.37
Pollution Index	62	61	124	220	239	509	1046	2520	2136	.92
Taxa	28	39	50	58	61	60	61	77	64	.75
BI-A	6.0	6.5	7.9	10.0	10.1	14.7	10.4	10.5	30.5	.83
BI-B	10.9	11.5	14.5	17.2	16.7	23.4	15.8	17.7	45.0	.82
BI-C	1.3	1.3	1.5	1.5	1.6	1.6	2.0	0.8	2.1	.35
BI-D	82.6	78.3	74.5	83.1	88.2	87.5	96.3	94.6	99.8	.91
BI-E	76.5	70.6	64.3	72.3	79.3	78.6	89.7	87.9	99.8	.92

*If N deviates from values shown by more than 10% then actual N is in parenthesis.
**5% level of significance >.754.
1% level of significance >.874.

Table 8

Mean Values of Physical, Chemical and Biological Parameters of Lake Samples Collected for Trophic Analysis Within Value Ranges of Indicated Parameter

Chlorophyll _a_ Turner Units

	Range of Values	7-14	15-29	30-44	45-59	60-89	90-119	120-179	180-239	>240	Corr. Coef.**
	N*	135	314	138	53	44	22	18	3	2	r(xy)
1	Temp. °C	15.8	19.6	21.1	22.5	21.4	19.2	16.9	21.2	15.1	-.37
2	Secchi-Ft.	4.9	3.9	3.5	3.4	2.6	2.2	1.7	1.8	1.3	-.90
3	Secchi-M	1.5	1.2	1.1	1.0	0.8	0.7	0.5	0.5	0.4	-.90
4	NH_3-N mg/m^3	65	73	63	60	66	64	252	107	200	.71
5	NO_2NO_3-N mg/m^3	197	163	135	116	144	90	92	88	41	-.90
6	Kjel-N mg/m^3	213	262	303	357	456	523	859	1227	900	.88
7	Inorg-N mg/m^3	263	236	199	176	210	154	344	195	241	.14
8	Org-N mg/m^3	148	189	240	297	391	459	608	1120	700	.81
9	Total-N mg/m^3	410	425	438	473	601	613	952	1315	941	.85
10	PO_4-P mg/m^3	16	13	11	17	30	22	52	81	108	.966
11	Total Sol-P mg/m^3	23	21	18	26	47	41	92	267	125	.74
12	Sol Org-P mg/m^3	7	8	8	9	16	20	38	186	18	.47
13	Particulate-P mg/m^3	14	21	20	26	47	73	80	193	172	.93
14	Total-P mg/m^3	35	42	38	52	94	114	173	460	297	.85
15	TN/TP	17.8	15.7	15.6	14.1	11.8	6.8	6.1	4.3	3.4	-.78
16	Inorg N/Sol-P	18.0	16.6	15.6	12.0	9.3	6.1	4.9	2.4	2.2	-.92
17	Alk mg/l	15(55)	17(141)	20(79)	22(25)	20(26)	22(17)	28(11)	27	27	-.31
18	Cond μmhos	65(54)	72(156)	103(94)	141(32)	102(31)	154	243(15)	508	272	.82
19	Cell Den no/ml	1206	2560	6732	9155	9394	17194	25849	60203	33680	.82
20	Biovol mm^3/m^3	1028	1211	2558	3862	3826	7713	8865	35595	19197	.79
21	Ln Cell Den	7.0059	7.3809	7.6895	8.0048	8.2743	9.0329	9.3889	10.1192	10.1596	.957
22	Ln Biovol	6.0365	6.6110	7.4567	7.8001	7.9809	8.7943	8.7477	10.1222	9.8347	.92
23	Chlor _a_-Turner Units(x)	12	21	36	51	76	103	144	184	262	-
24	Prod mgC/m^3/hr	12(33)	20(118)	44(81)	70(32)	79(31)	120	174(15)	300	243	.929

*If N deviates from values shown by more than 10% then actual N is in parenthesis.

**5% level of significance >.666
1% level of significance >.798.

indication of lack of sensitivity at these levels. However, outstanding correlations are noted with the Secchi depth-TSI as well as that of the chlorophyll and total phosphorus TSI's. The correlation, significant at the 5% level, with turbidity would possibly be indicative of a measurement of biological particulates containing chlorophyll as well as response to other fluorescing materials. The relation to Pollution Index is also very strong as well as with the biological indices D and E. The comparisons with the physical and chemical parameters shows very highly correlated relationships with PO_4-P and particulate-P as well as the measurement of productivity. In the comparison with conductivity the correlation was not as strong as has been previously demonstrated with the chlorophyll a by extraction, although it is still greater than the 1% level of significance.

Total Phosphorus

A key measure of any aquatic environment and its trophic state is the quantity of total phosphorus in the system. Although it is widely recognized that phosphorus cycles rapidly through many forms, it is the total reservoir of phosphorus that must be available for the nutrient flux required to support the microflora. In twelve subsets, over a range of 1 to more than 300 mg/m^3, the relationship of total phosphorus to the various trophic indices are examined (Table 9). The expected negative correlation with Secchi depth is indicated. It is just at the 5% level of significance primarily because the changes in quantity with increase in Secchi depth lack resolution above 50 mg/m^3 total phosphorus. Extremely high correlation is shown for chlorophyll a as well as with the bioassay indices of reseeded algae grown in water samples pretreated either by autoclaving or filtration. The correlation with cell density or cell volume are equally striking as well as with the Pollution Index. Except for the biological index E the others show correlations coefficients that are above the 1% level of significance. Key to the importance of phosphorus as a trophic state indicator is the exemplary correlation relationships found not only for the direct measures of cell materials, e.g. density and biovolume as well as the response of the specific population identified in the Pollution Index but also the manner in which the algal assay procedure responded to the proportional amount of phosphorus in the test sample.

Table 9

Mean Values of Trophic State Indices
Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

TP (Total Phosphorus) mg/m³

Range of Values	1-9	10-19	20-29	30-39	40-49	50-69	70-89	90-109	110-149	150-199	200-299	>300	Corr. Coef. r(xy)**
N*	33	191	184	108	65	96	61	27	42	18	15	11	
Secchi-M	2.4	1.7	1.4	1.1	1.0	0.7	0.6	0.6	0.5	0.6	0.5	0.6	-.53
Chlor a mg/m³	12(16)	7(49)	12(41)	13(22)	21(12)	25(15)	20(17)	17(6)	35(13)	41(7)	35	102(6)	.962
TP mg/m³ (x)	6.6	13	21	32	41	56	77	96	123	168	235	464	-
SD-TSI	48.2	52.9	56.2	59.5	59.9	65.3	68.9	69.2	70.0	68.4	72.5	67.3	.57
CH-TSI	50.1(16)	47.1(49)	52.5(41)	54.2(22)	56.6(12)	59.6(15)	56.2(17)	54.7(6)	60.8(13)	62.4(7)	56.6	73.0	.86
TP-TSI	26.9	36.5	44.9	50.5	54.3	58.8	63.1	66.3	70.2	74.4	79.0	84.3	.80
Color Pt Units	13(13)	29(57)	42(53)	20(31)	18(17)	33(25)	34(22)	28(9)	83(22)	78(9)	126	31	.37
Turb. JTU	6(28)	6	8(98)	12(58)	11(28)	19(43)	27(27)	42(10)	40(27)	20(12)	20	41	.62
Aut. Wgt.	1.3(8)	1.6(61)	3.0(45)	3.8(36)	4.7(22)	8.5(31)	9.9(14)	10.3(10)	13.0(17)	12.7(4)	14.7(5)	26.8(2)	.962
Filt. Wgt.	0.4(8)	0.3(61)	1.1(45)	1.6(36)	1.7(22)	4.0(31)	1.5(14)	4.7(10)	5.6(17)	2.2(4)	10.0(5)	15.5(2)	.93
Cell Den. no./ml	3260	3090	3820	4572	5205	4551	4997	6076	7211	12569	14739	27759	.991
Biovol. mm³/m³	1763	1802	1560	2071	2671	2071	2245	2629	3015	4318	5161	14260	.964
Shan-Weaver	3.372	3.432	3.535	3.660	3.643	3.747	3.844	3.780	3.984	3.802	3.674	3.747	.38
Evenness	0.642	0.640	0.661	0.666	0.649	0.682	0.704	0.702	0.717	0.694	0.700	0.674	.35
Pollution Index	84	66	78	102	166	97	136	119	244	280	403	1163	.967
Taxa, no. sp.	39	39	40	45	47	44	45	41	47	45	44	52	.72
BI-A	6.6	5.6	6.3	7.2	8.1	8.1	8.7	9.7	10.1	9.3	9.2	10.6	.74
BI-B	11.9	9.4	10.7	12.2	14.4	15.0	16.3	16.6	17.4	15.4	14.8	17.5	.62
BI-C	1.1	1.5	1.3	1.3	1.2	1.5	1.7	1.4	1.6	1.5	1.4	1.3	.04
BI-D	64.6	73.7	75.2	78.5	84.1	83.4	84.8	81.7	92.5	90.2	87.8	97.9	.78
BI-E	53.2	67.1	63.8	67.3	73.7	77.0	78.7	71.5	84.2	81.8	78.8	95.3	.81

*If N deviates from values shown by more than 10% then actual N is in parenthesis.
**5% level of significance >.553
1% level of significance >.684.

Conductivity

Conductivity over a range of seven to more than 300 μmhos/cm and divided into seven subsets of values is examined in its relationship to trophic indices in Tables 10 and 11. It clearly becomes a candidate as an important trophic state indicator by the strong correlations shown with the primary measures of response to nutrient enhancement cell growth and biovolume. Strong correlations are also noted for chlorophyll a, and the Pollution Index. In Table 11, the strong correlations are also noted for Kjel-N, organic nitrogen, and total nitrogen all measures of biological materials. The correlations with chlorophyll a-Turner and productivity are also strong.

Trophic State-Indices (Carlson)

These indices calculated from the basic measurements of Secchi depth, chlorophyll a and total phosphorus provide a range of values from 0-100 in 10 unit intervals and are scaled to known trophic conditions. The intent was to provide a sensitive index each increasing in scale value as the trophic state changed from water of high quality, oligotrophic to water of low quality, eutrophic. Although each is independent, they are parallel in scale and can be cross compared in their relationships to trophic state. The SD-TSI, CH-TSI and TP-TSI are compared to other trophic state indices over the range of values determined in this set of observations (Tables 12, 13, 14). The correlations for the trophic state index computed from Secchi depth tend to be somewhat low or below significant levels, few attaining any unusual level except with total phosphorus and with the actual Secchi depth measurement.

The CH-TSI derived from chlorophyll a determinations and organized in subsets of 10 unit intervals is highly correlated with both the direct Secchi measurement as well as the SD-TSI and the TP-TSI. Very strong correlations are also noted for cell density although not as good as that with biovolume. The Shannon-Weaver diversity index is strongly correlated in contrast with the essentially non-existent correlation of the Evenness Index. The Pollution Index barely reaches the 5% level of significance but taxa and the biological indices A, B, C, D and E are all well correlated.

With few exceptions nearly all of the other trophic state indices are well correlated with the TP-TSI. Exceptions include comparatively poor correlation with Shannon-Weaver, Evenness diversity indices, number of taxa and the biological index C. The low but still significant correlation with cell

Table 10

Mean Values of Trophic State Indices
Derived from Lake Samples Collected for Trophic Analysis
Arranged Within Value Range of Given Index

Conductivity μmho/cm

Range of Values	7-19	20-49	50-99	100-149	150-199	200-299	>300	Corr. Coef. r(xy)**
N*	17	47	245	120	17	19	11	
Secchi-M	3.16	0.99	1.40	1.21	0.84	0.63	0.47	-.63
Chlor a	2.9	8.0(23)	13(80)	18(55)	38(12)	49	83(8)	.981
Total-P	18	85	42	37	82	136	290	.954
SD-TSI	44.1	64.2	57.4	57.9	63.5	66.7	70.7	.72
CH-TSI	40.4	47.6(23)	52.5(80)	57.1(55)	64.1(12)	66.0	59.9(8)	.84
TP-TSI	40.6	56.4	48.2	48.1	60.9	66.7	78.1	.90
Color	14	47	46.5(117)	34.8(56)	28.3	37.8(17)	17.0(8)	-.41
Turbidity	3	24	3	2	6	18	4	-.15
Aut. Wgt.	-	9.1(19)	4.3(8)	4.9(36)	8.4(5)	4.4(3)	15.6(3)	.75
Filt. Wgt.	-	2.1(19)	1.9(81)	1.5(36)	0.8(5)	1.7(3)	12.7(3)	.90
Cell Density	999	2043	4379	8155	10751	24927	39697	.974
Biovolume	1571	2463	1779	3101	5545	9197	18767	.987
Shan-Wea	2.944	3.275	3.506	3.859	4.344	3.971	4.223	.73
Evenness	0.612	0.659	0.662	0.663	0.727	0.674	0.720	.72
Pollution Index	7	44	120	163	387	591	2095	.984
Taxa	24	30	40	54	62	52	63	.75
BI-A	4.5	4.9	7.0	7.3	11.7	13.5	10.1	.61
BI-B	7.1	9.3	11.9	12.9	19.4	20.9	15.2	.53
BI-C	0.9	1.0	1.3	1.3	1.8	1.6	1.3	.37
BI-D	54.4	55.6	77.6	74.1	70.7	91.8	78.9	.57
BI-E	39.8	55.3	66.4	61.1	84.4	83.2	71.8	.54

*If N deviates from values shown by more than 10% then actual N is in parenthesis.
**5% level of significance >.707
1% level of significance >.834.

Table 11

Mean Values of Physical, Chemical and Biological Parameters of Lake Samples Collected for Trophic Analysis Within Value Range of Indicated Parameter

Conductivity μmho/cm

Range of Values	7-19	20-49	50-99	100-149	150-199	200-299	>300	Corr. Coef. r(xy)**
N*	17	47	245	120	17	19	11	
Temp °C	24.0	17.9	19.3	21.6	17.8	18.7	16.8	-.61
Secchi-Ft.	10.4	3.2	4.6	4.0	2.8	2.2	1.6	-.62
Secchi-M	3.16	0.99	1.40	1.21	0.84	0.63	0.47	-.63
NH_3-N mg/m^3	22	102	60	57	66	140	325	.94
NO_2NO_3-N mg/m^3	41	192	117	88	109	65	118	.01
Kjel-N mg/m^3	186	325	302	316	418	676	1076	.978
Inorg-N mg/m^3	63	294	177	145	175	205	474	.81
Org-N mg/m^3	165	223	242	258	352	536	750	.973
Total-N mg/m^3	228	223	419	403	527	741	1267	.991
PO_4-P mg/m^3	4.0	19	12	11	15	39	67	.95
Total Sol-P mg/m^3	9.4	39	19	17	25	51	166	.94
Sol Org-P mg/m^3	5.4	20	7	6	10	13	103	.90
Particulate P mg/m^3	8.2	46	23	21	57	84	124	.92
Total-P mg/m^3	18	85	42	37	82	136	290	.954
TN/TP	14.8	11.1	16.4	17.3	8.9	10.8	5.0	-.77
Inorg N/Sol P	9.5	11.6	15.6	13.8	11.9	8.3	3.9	-.77
Alkinity mg/l	4.5	8.1	19	27(99)	24(14)	25	26	.64
Conductivity μmho (x)	14	39	76	116	167	225	510	-
Cell Density no/ml	999	2043	4379	8511	10751	24927	39697	.975
Biovolume mm^3/m^3	1571	2463	1779	3101	5545	9197	18767	.987
Ln Cell Density	6.7028	6.7003	7.5876	8.2123	8.1278	9.6602	8.9415	.85
Ln Biovolume	7.0366	6.6053	6.8200	7.5607	8.3980	8.6439	9.3610	.90
Chlor a Turner Units	12	28	31(205)	41(97)	94	108	142	.92
Prod mg C/m^3/hr	5.0(1)	25(19)	32(174)	48(95)	96	155(17)	202	.94

*If N deviates from values shown by more than 10% then actual N is in parenthesis.

**5% level of significance >.707

1% level of significance >.834.

Table 12

Mean Values of Trophic State Indices
Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

SD-TSI (Secchi Depth - Trophic State Index)

Range of Values	30-39	40-49	50-59	60-69	70-79	80-89	>90	Corr. Coef. r(xy)**
N*	6	107	311	318	74	24	2	
Secchi-M	3.7	2.5	1.4	0.8	0.3	0.2	0.5	-.89
Chlor a mg/m^3	2(4)	4(28)	12(79)	24(71)	47(24)	20(5)	6.3	.38
TP mg/m^3	20	15	26	62	117	117	140	.958
SD-TSI (x)	36.8	46.2	54.9	63.6	74.9	81.9	94.5	-
CH-TSI	38.8(4)	41.9(28)	52.8(79)	59.2(71)	60.2(24)	50.6(5)	44.5	.37
TP-TSI	40.5	37.8	43.9	55.8	66.4	66.8	59.0	.85
Color Pt Units	10(4)	12(26)	19(91)	47(101)	85(41)	35(6)	166	.83
Turb. JTU	2(4)	4(91)	8	15(148)	40(50)	52(7)	19	.70
Aut. Wgt.	2.5(2)	1.5(24)	2.9(97)	6.5(99)	11.6(28)	24.4(4)	-	.87
Filt. Wgt.	3.2(2)	0.6(24)	1.0(97)	2.8(99)	4.2(28)	9.3(4)	-	.72
Cell Den. no./ml	770	1914	4170	6523	6648	3688	470***	.18 (.71)
Biovol. mm^3/m^3	1324	1179	2068	2688	3538	1383	76***	-.14 (.48)
Shan-Weaver	3.426	3.250	3.673	3.607	4.024	3.525	2.426	-.35
Evenness	0.682	0.640	0.657	0.661	0.729	0.753	0.724	.76
Pollution Index	29	41	95	159	266	73	0	.12
Taxa, no. sp.	28	32	46	44	45	24	10	-.43
BI-A	5.9	5.1	6.8	8.2	9.1	4.3	1.5	-.39
BI-B	9.8	8.0	11.4	14.5	16.8	10.1	3.5	-.18
BI-C	1.0	1.3	1.4	1.5	1.1	1.7	0.3	-.32
BI-D	49.4	72.9	75.7	84.6	81.2	82.7	25.0	-.21
BI-E	43.2	57.4	66.5	77.6	74.3	78.7	39.3	.14

*If N deviates from values shown by more than 10% then actual N is in parenthesis.
**5% level of significance >.666
1% level of significance >.798.
***Not used in calculating corr. coef. in ( ).

Table 13

Mean Values of Trophic State Indices
Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

CH-TSI (Chlorophyll Trophic State Index)

Range of Values	29-39	40-49	50-59	60-69	70-79	>80	Corr. Coef. r(xy)**
N*	24	48	64	63	12	2	
Secchi-M	2.1	1.6	1.2	0.9	0.4	0.4	-.984
Chlor a mg/m^3	2	4	11	29	79	166	.88
TP mg/m^3	37	46	45	62	24	634	.79
SD-TSI	53.5	57.3	58.0	62.5	72.3	74.0	.963
CH-TSI (x)	35.9	44.3	54.4	63.2	72.9	81.0	-
TP-TSI	44.0	48.7	48.8	55.4	76.1	92.5	.92
Color Pt Units	30(18)	37	41	39	26	15	-.59
Turb. JTU	14	16	10	13	27	21	.62
Aut. Wgt.	3.5(3)	0.1(1)	0.4(4)	1.5(1)	-	-	-.46
Filt. Wgt.	0.1(3)	0.6(1)	0.1(4)	0.1(1)	-	-	-.29
Cell Den. no./ml	966	2223	9358	15881	36066	47313	.956
Biovol. mm^3/m^3	771	1550	3396	5639	9689	49835	.76
Shan-Weaver	3.583	3.373	3.639	4.035	4.168	4.369	.93
Evenness	0.708	0.647	0.637	0.675	0.686	0.717	.33
Pollution Index	23	33	101	312	887	4080	.77
Taxa, no. sp.	32	36	52	62	68	70	.975
BI-A	4.4	5.4	7.6	16.5	17.9	17.9	.969
BI-B	7.5	9.9	13.6	16.6	25.6	29.4	.978
BI-C	0.8	1.1	1.2	1.4	1.1	2.0	.80
BI-D	64.4	61.9	60.5	77.4	94.8	100.0	.90
BI-E	48.0	56.6	48.2	67.4	83.2	100.0	.91

*If N deviates from values shown by more than 10% then actual N is in parenthesis.
**5% level of significance >.754
1% level of significance >.874

Table 14

Mean Values of Trophic State Indices Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

TP-TSI (Total Phosphorus Trophic State Index)

Range of Values	20-29	30-39	40-49	50-59	60-69	70-79	80-89	>90	Corr. Coef. r(xy)**
N*	17	141	265	207	157	44	15	3	
Secchi-M	2.0	1.9	1.4	1.0	0.6	0.5	0.5	0.8	.87
Chlor a mg/m^3	21(7)	5(27)	11(71)	18(42)	23(36)	36(16)	64(10)	106	.84
TP mg/m^3	5.1	11	27	39	82	163	297	733	.83
SD-TSI	50.6	51.6	56.0	60.6	68.5	70.1	71.2	62.7	.82
CH-TSI	57.4(7)	44.1(27)	51.1(71)	56.0(42)	57.7(36)	58.3(16)	67.1(10)	67.5	.79
TP-TSI (x)	23.4	34.0	44.1	53.5	63.6	73.8	83.7	95.7	-
Color Pt Units	12(7)	24(27)	39(90)	21(59)	35(56)	94.7(23)	104.6	23.5	.54
Turb. JTU	5(12)	6(85)	8(164)	11(95)	31(68)	30(33)	32	15	.69
Aut. Wgt.	1.2(4)	1.3(46)	2.9(70)	4.7(65)	10.7(52)	4.2(14)	21.7(3)	-	.80
Filt. Wgt.	0.4(4)	0.3(46)	1.0(70)	2.1(65)	3.8(52)	6.8(14)	11.2(3)	-	.92
Cell Den. no./ml	4188	2596	3733	5010	5216	10912	23845	22663	.86
Biovol. mm^3/m^3	1558	1358	1807	2399	2286	3968	8087	27008	.74
Shan-Weaver	3.654	3.338	3.515	3.720	3.820	3.842	3.758	3.814	.70
Evenness	0.655	0.638	0.655	0.666	0.702	0.700	0.699	0.651	.48
Pollution Index	104	62	77	131	121	266	859	1543	.81
Taxa, no. sp.	48	35	40	47	43	46	48	59	.66
BI-A	7.5	5.4	6.2	7.8	9.0	9.3	10.3	13.6	.88
BI-B	13.2	9.1	10.4	13.8	16.3	15.8	16.1	22.1	.84
BI-C	1.3	1.5	1.2	1.3	1.6	1.5	1.4	1.3	.14
BI-D	74.8	72.6	75.0	80.7	84.6	93.4	87.7	100.0	.93
BI-E	67.9	65.1	64.5	70.8	77.8	85.4	82.5	99.9	.91

*If N deviates from values shown by more than 10% than actual N is in parenthesis.

**5% level of significance >.666
1% level of significance >.798.

volume may be due in part to a lack of sensitivity over the range of TP-TSI scaled.

Color

The color of water and its effect on transparency, its relationship to humic materials and associations with acidic waters has caused this parameter to be examined in relationship to the response of the various trophic state indices. It would appear that color per se has little or no relationship to any of the other trophic indices (Table 15). However, the relationship to cell density and biovolume suggest that at higher color levels these decrease in proportion to the amount of color present. The specialized cases of highly colored waters and their role in trophic classification is one that generally requires individual analysis of the particular body of water.

Turbidity

Similar to the rational for the examination of the relationship between color and the various trophic indices, the data for turbidity was also organized (Table 16). No attempt was made to discriminate between turbidity due to biological particulates and that due to suspended sediments. The correlation coefficients suggest that at the higher turbidities, over 40 JTU, this could very well be primarily sediment particulates. The significant relationship with total phosphorus as well as TP-TSI would also appear to argue that a proportion of phosphorus and its relationship to turbidity are materials of nonbiological composition. Except for the Evenness diversity index all the other biological criteria of changing quality appear to be nonrelated in any significant way to turbidity. The possibility of the phosphorus relationship to turbidity may be creating the marginal correlation for the Evenness diversity index and BI-E.

Autoclaved and Filtered Weight, Biomass Determination

In the development of the algal assay procedure for determination of limiting nutrients in surface waters, one important step in the preparation of sample is the removal of existing viable algal cells. This step can be achieved either by autoclaving of the raw water sample or filtration through membrane filters. In the latter procedure the filtrate then becomes a media containing the soluble

Table 15

Mean Values of Trophic State Indices Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

Color Pt Units

Range of Values	1-9	10-19	20-39	40-79	80-159	160-299	>300	Corr. Coef. r(xy)**
N*	70	107	40	30	19	9	5	
Secchi-M	1.6	1.2	0.7	0.8	0.9	0.7	0.3	-.76
Chlor a mg/m³	8(49)	29(87)	16(26)	18(13)	23(8)	9(7)	23(4)	.14
TP mg/m³	26	67	113	122	44	33	166	.55
SD-TSI	53.6	60.2	69.2	65.1	61.9	69.3	75.6	.77
CH-TSI	48.2(49)	59.5(87)	52.5(26)	51.5(13)	54.5(8)	49.3(7)	59.8(4)	.44
TP-TSI	45.3	52.4	63.2	62.0	51.8	47.7	79.2	.69
Color Pt Units (x)	6	14	28	60	100	207	481	-
Turb. JTU	7	15	31	33	6	9	7	-.41
Aut. Wgt.	3.8(12)	3.6(15)	8.5(10)	12.1(13)	2.9(7)	0.0(1)	-	-.49
Filt. Wgt.	0.7(12)	1.1(15)	0.4(10)	4.3(13)	0.9(7)	0.2(1)	-	-.18
Cell Den. no./ml	7981	13234	9158	3028	3040	911	3579***	-.53(-.80)
Biovol. mm³/m³	2390	5512	3294	1651	1849	896	2545***	-.29(-.69)
Shan-Weaver	3.627	3.868	3.666	3.500	2.692	2.856	3.388	-.32
Evenness	0.648	0.659	0.682	0.680	0.595	0.662	0.657	-.04
Pollution Index	99	287	152	100	66	6	560***	.67(-.73)
Taxa, no. sp.	48	57	43	34	23	20	34	-.44
BI-A	7.3	10.2	8.0	7.7	3.0	3.6	7.6	-.19
BI-B	11.9	17.6	15.0	13.3	5.1	6.6	9.2	-.48
BI-C	1.0	1.3	1.2	1.0	0.8	0.9	1.8	.66
BI-D	67.0	75.0	75.5	70.0	32.2	46.1	97.5	.25
BI-E	52.1	65.4	71.3	64.6	34.5	44.1	95.1	.53

*If N deviates from values shown by more than 10% then actual N is in parenthesis.
**5% level of significance >.707
1% level of significance >.834.
***Value not used in calculating r in parenthesis.

Table 16

Mean Values of Trophic State Indices
Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

Turbidity JTU

Range of Values	1-5	6-12	13-19	20-29	30-39	40-69	70-89	>90	Corr. Coef. r(xy)**
N*	159	159	77	32	25	11	8	5	
Secchi-M	2.1	1.2	0.9	0.6	0.4	0.3	0.3	0.3(4)	-.68
Chlor a mg/m^3	7(66)	17(70)	23(40)	52(17)	56(10)	5(5)	4.7(4)	1(1)	-.42
TP mg/m^3	29	43	57	104	142	92	115	191	.85
SD-TSI	51.0	57.8	61.5	67.4	72.7	75.5	78.1	78.3(4)	.84
CH-TSI	46.3(66)	55.6(70)	59.5(40)	65.7(17)	60.2(10)	45.6(5)	46.3(4)	31.0(1)	-.74
TP-TSI	42.3	48.1	54.1	62.5	67.5	64.6	68.5	73.8	.83
Color Pt Units	60(82)	39(89)	15(50)	21(21)	37(17)	31(9)	41(7)	43	.13
Turb. JTU (x)	4	9	16	24	34	51	81	121	-
Aut. Wgt.	2.2(37)	4.4(54)	7.2(24)	12.3(7)	11.4(8)	7.7(5)	16.3(3)	11.9(3)	.67
Filt. Wgt.	0.6(37)	1.6(54)	4.6(24)	3.5(7)	2.8(8)	1.5(5)	0.1(3)	0.2(3)	-.55
Cell Den. no./ml	2847	8241	9438	13650	14166	1077	677	318	-.58
Biovol. mm^3/m^3	1415	3317	3899	6705	3933	835	426	242	-.60
Shan-Weaver	3.200	3.659	4.009	4.0347	3.757	4.120	4.215	3.879	.47
Evenness	0.632	0.653	0.692	0.693	0.708	0.759	0.807	0.807	.94
Pollution Index	71	145	229	398	349	27	31	26	-.48
Taxa, no. sp.	33	48	54	57	43	42	37	26	-.64
BI-A	5.0	7.8	8.7	10.3	9.0	7.7	6.4	3.7	-.57
BI-B	7.7	13.1	15.3	17.9	15.0	15.8	15.6	10.2	-.07
BI-C	1.1	1.3	1.6	1.2	1.1	0.9	1.2	0.9	-.55
BI-D	63.1	72.9	87.1	91.2	89.1	73.1	91.5	89.8	.51
BI-E	50.8	62.7	74.4	81.1	83.1	65.6	88.9	86.8	.68

*If N deviates from values shown by more than 10% then actual N is in parenthesis.

**5% level of significance >.666
1% level of significance >.798.

nutrients representative of the time of sampling. Subsequent reseeding with a test species, e.g. Selenastrum capricornutum, and culture under controlled temperature and light conditions defines by the biomass formed the growth potential of this nutrient quantity. In the procedure which destroys all viable cells by autoclaving, a larger nutrient pool is created by the solubilization of nutrient materials from both cellular as well as non-cellular sources. This nutrient pool is generally cleansed of residual particulates by a subsequent filtration. The reseeding of the autoclaved sample with the test alga and culture under controlled conditions provides a demonstration of the total nutrient pool. This assumes that normal processes of biological degradation or solubilization would have eventually released the nutrient resources for algal growth. Thus filtration provides the media that reflects the existing nutrient pool and autoclaving the potential nutrient pool. These control growth procedures do not include the addition of nitrogen or phosphorus nutrient spikes.

These growth determining procedures may also be used as an indicator of trophic condition and have been included in Tables 17 and 18 to illustrate the relationship between their range of values and other trophic indicators. It is clear that they are highly correlated, at very significant levels, with each other. The autoclaved control growth also shows high correlation with total phosphorus, as might be expected due to the treatment procedure, but shows little or no correlation with any other of the trophic indicators except Secchi depth. The growth in the filtered sample, reflecting the magnitude of the existing nutrient pool, is also highly correlated with total phosphorus; somewhat marginally to Secchi depth; fairly significantly with the Evenness diversity index; negatively correlated at significant levels with taxa and the biological index D.

Over the range of values for growth in either autoclaved or filtered samples few parallelisms are noted with other trophic indicators that correlate significantly. However, when these same values for both autoclaved and filtered samples are compared to nutrient levels and other measures of productivity the correlations are strong and more significant (Tables 19, 20). The noncorrelated relationships are the exception rather than the rule. The filtered samples show a series of noncorrelated relationships that includes kjeldahl nitrogen as well as organic nitrogen. The correlation with ratio of inorganic nitrogen to soluble phosphorus is almost at significant levels. Chlorophyll is noncorrelated but productivity does show a strong positive correlation. The autoclaved

Table 17

Mean Values of Trophic State Indices
Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

Filtered Weight mg/1

Range of Values	0.01-0.1	0.2-1.9	2.0-4.9	5.0-7.9	8.0-10.9	11.0-16.9	17.0-22.9	>23.0	Corr. Coef. r(xy)**
N*	115	72	40	9	5	9	2	3	
Secchi-M	1.2	1.2	0.9	0.6	1.0	0.5	0.6	0.6	-.72
Chlor a mg/m^3	8	9(1)	-	-	-	-	-	-	-
TP mg/m^3	33	44	72	55	53	101	78	248	.88
SD-TSI	58.3	58.8	62.4	67.0	61.2	70.7	66.0	66.7	.66
CH-TSI	47.8(8)	43.0(6)	-	-	-	-	-	-	-
TP-TSI	45.9	48.9	58.2	56.9	55.2	64.8	62.0	78.0	.93
Color Pt Units	34(29)	42(21)	38(4)	-	-	19(1)	-	65(2)	.52
Turb. JTU	17(58)	14(49)	14(22)	27(3)	25	22(4)	-	14	-.06
Aut. Wgt.	3.0	3.7	7.7	10.3	9.6	21.2	16.9	39.0	.959
Filt. Wgt.(x)	0.09	0.8	3.2	5.6	9.7	14.9	18.9	29.4	-
Cell Den. no./ml	3502	4830	6328	3345	1656	2409	591	5312	-.18
Biovol. mm^3/m^3	2266	2206	3839	1964	897	1482	396	2137	-.19
Shan-Weaver	3.749	3.790	3.556	3.762	3.661	3.616	3.988	3.841	.43
Evenness	0.676	0.681	0.661	0.688	0.666	0.674	0.783	0.736	.69
Pollution Index	135	262	283	83	93	143	86	413	.35
Taxa, no. sp.	45	45	51	42	40	38	31	37	-.79
BI-A	7.5	8.2	7.6	5.6	8.4	7.7	12.0	8.2	.42
BI-B	13.0	14.2	13.3	10.0	13.2	13.5	21.0	11.7	.20
BI-C	1.5	1.3	1.4	1.3	1.0	1.5	3.8	0.8	.16
BI-D	79.3	82.5	74.4	86.7	78.9	80.1	94.7	98.0	.79
BI-E	73.7	74.0	67.2	78.5	68.8	70.8	97.6	85.9	.62

*If N deviates from values shown more than 10% then actual N is in parenthesis.

**5% level of significance >.666
1% level of significance >.798.

Table 18

Mean Values of Trophic State Indices
Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

Autoclaved Weight mg/l

Range of Values	0.01-0.1	0.2-1.9	2.0-4.9	5.0-7.9	8.0-10.9	11.0-16.9	17.0-22.9	>23.0	Corr. Coef. r(xy)**
N*	47	54	63	32	24	19	5	10	
Secchi-M	1.3	1.5	1.1	0.9	0.8	0.7	0.4	0.5	-.84
Chlor a mg/m^3	6(6)	15(2)	-	-	2(1)	-	-	-	-.49
TP mg/m^3	27	23	46	68	55	71	100	151	.979
SD-TSI	56.6	55.3	58.9	61.8	65.2	66.7	72.2	70.7	.88
CH-TSI	45.7(6)	56.0(2)	-	-	39.0(1)	-	-	-	-.74
TP-TSI	41.5	42.5	51.7	55.9	55.5	60.4	62.4	70.4	.93
Color Pt Units	49(13)	19(11)	50(12)	41	20(7)	32(5)	65	67(3)	.59
Turb. JTU	7(22)	8(32)	13(36)	18	27(16)	36(8)	35	314(5)	.78
Aut. Wgt. (x)	0.08	1.1	3.2	6.3	9.5	13.3	19.1	33.4	-
Filt. Wgt.	0.16	0.5	1.1	3.1	2.5	4.4	7.4	16.1	.982
Cell Den. no./ml	2833	5253	3639	7256	3429	3327	4794	3244	-.20
Biovol. mm^3/m^3	1787	2304	2957	3112	2370	1377	4735	1456	-.05
Shan-Weaver	3.709	3.598	3.766	3.888	3.630	3.819	3.625	3.776	.13
Evenness	0.687	0.643	0.679	0.697	0.658	0.711	0.655	0.719	.46
Pollution Index	111	231	196	288	122	191	227	263	.41
Taxa, no. sp	42	46	45	46	42	40	46	37	-.63
BI-A	6.1	7.4	7.3	8.9	8.2	10.3	9.5	8.6	.56
BI-B	10.8	12.0	12.7	15.9	15.6	16.7	18.3	14.4	.52
BI-C	1.5	1.5	1.2	1.8	1.2	1.5	1.3	1.7	.24
BI-D	80.3	76.5	75.3	88.1	81.3	90.1	88.0	77.7	.15
BI-E	73.9	69.5	66.7	82.0	75.4	88.5	69.3	70.3	-.04

*If N deviates from values shown more than 10% then actual N is in parenthesis.

**5% level of significance >.666
1% level of significance >.798.

Table 19

Mean Values of Physical, Chemical and Biological Parameters
Derived from Lake Samples Used in the Algal Assay
Value Ranges of Growth in Samples Prepared by Filtration

Range of Values	mg/1								Corr. Coef. r(xy)**
	0.01-0.1	0.2-1.9	2.0-4.9	5.0-7.9	8.0-10.9	11.0-16.9	17.0-22.9	>23.0	
N*	115	72	40	9	5	9	2	3	
NH_3-N mg/m^3	63	74	94	56	75	159	160	473	.89
NO_2NO_3-N mg/m^3	145	136	161	259	183	391	408	372	.86
Kjel-N mg/m^3	288	344	572	413	356	393	275	967	.62
Inorg N mg/m^3	209	210	254	316	258	550	568	845	.973
Org N mg/m^3	225	270	478	357	281	234	115	493	.14
Total N mg/m^3	433	479	732	673	539	784	683	1338	.86
PO_4-P mg/m^3	7.5	15	20	18	25	49	32	150	.88
Total Sol-P mg/m^3	15	23	32	34	39	70	48	195	.88
Sol Org P mg/m^3	7	8.0	12	16	14	21	15	78	.84
Part-P mg/m^3	18	21	42	21	14	30	30	53	.66
Total-P mg/m^3	33	44	72	55	53	101	78	248	.88
TN/TP	19.4	17.4	15.2	15.3	13.1	8.9	9.5	7.1	-.94
Inorg N/Sol P	20.3	15.8	11.4	11.2	9.3	10.1	13.1	7.4	-.68
Chlor a-Turner Units	32	37(60)	46(27)	34(5)	22(5)	29	14	68	.32
Prod mg C/m^3/hr.	41(50)	47(32)	58(34)	47(5)	31(2)	56(3)	-	199(1)	.87

*If N deviates from values shown more than 10% then actual N is in parenthesis.
**5% level of significance >.666
1% level of significance >.798.

Table 20

Mean Values of Physical, Chemical and Biological Parameters
Derived from Lake Samples Used in the Algal Assay
Value Ranges of Growth in Samples Prepared by Autoclaving

mg/1

Range of Values	0.01-0.1	0.2-1.9	2.0-4.9	5.0-7.9	8.0-10.9	11.0-16.9	17.0-22.9	>23.0	Corr. Coef. r(xy)**
N*	47	54	63	32	24	19	5	10	
NH_3-N mg/m^3	50.0	58.9	71.8	81.6	80.7	105.3	98.0	317.0	.91
NO_2NO_3-N mg/m^3	135.1	82.6	129.8	143.7	249.7	293.7	425.0	386.5	.88
Kjel-N mg/m^3	275.7	275.2	402.7	509.5	311.7	371.6	512.0	643.0	.82
Inorg N mg/m^3	185	141	202	225	330	399	532	704	.987
Org N mg/m^3	226	216	330	428	231	266	414	326	.36
Total Nmg/m^3	411	358	532	653	561	665	937	1030	.94
PO_4-P mg/m^3	11	6.2	14	18	12	25	48	63	.957
Total Sol-P mg/m^3	15	10	22	29	27	40	63	100	.987
Sol Org P mg/m^3	3.7	4.0	9.4	12	16	15	16	33	.962
Part-P mg/m^3	12	13	24	39	29	34	37	51	.87
Total-P mg/m^3	27	23	46	68	55	71	100	151	.979
TN/TP	22.9	19.7	16.7	16.3	13.6	11.1	13.6	8.2	-.88
Inorg N/Sol P	22.9	17.2	13.6	12.8	12.7	22.9	15.5	11.7	-.38
Chlor a-Turner Units	28	33(48)	35(48)	54(23)	32(20)	341(16)	58	41.9(8)	.42
Prod mg C/m^3/hr.	31(18)	36(30)	41(33)	93(20)	31(13)	46(6)	77(3)	98(4)	.70

*If N deviates from values shown more than 10% then actual N is in parenthesis.

**5% level of significance >.666
1% level of significance >.798.

treatment shows lack of correlation only with organic nitrogen, the ratio of inorganic nitrogen to soluble phosphorus and to chlorophyll. All other measurements are strongly correlated and some at very significant levels. It would appear that these algal growth indicators, of either existing or potential nutrients, are effective in describing those values but do not serve well as a trophic state indicator.

Cell Numbers and Volume

Basic to the use of an indicator of trophic quality or trophic state is the relationship of any suggested measure to the actual numbers and volume of cells present under the conditions of growth. The data pool of observations on cell density and cell volume were organized in 13 subsets for cell density and 12 subsets for cell volume. These range from as low as 5 cell units/ml to over 50,000 and for biovolume from a low of 10 mm^3/m^3 to over 30,000 mm^3/m^3 (Tables 21 and 22). It is clear that nearly all of the trophic state indices are correlated although some at much higher levels of significance. Cell density is highly correlated with chlorophyll a and total phosphorus and of the three TSI's (Carlson) the relationship is best with TP-TSI. The unusually good correlation with the pollution index argues again for the meaning rulness of this particular index and its indication of trophic quality. The correlations of biovolume parallel those of cell density. The exceptions in both cases being poor or no correlation with aut. wgt. and filt. wgt. and in the case of cell density with the biological indices. However, improves over the range of values for biovalue the relationship to the biological indices and BI-E.

Diversity Indices

The two classic diversity indices describing relationship of different numbers of species to the total population, Shannon-Weaver and Evenness are organized in the usual steo sequences through the observed range of values and related to other indices of trophic quality (Tables 23, 24). It is of interest to observe that whereas Shannon-Weaver is negatively correlated with Secchi depth, higher diversity in less transparent waters and is positively correlated with chlorophyll a, Evenness has the same negative correlation with Secchi depth but is not correlated with chlorophyll a. However, its regression line shows a curvilinear relationship with a peak value in the

Table 21

Mean Values of Trophic State Indices
Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

Cell Density no./ml

Range of Values	5-299	300-599	600-999	1000-1999	2000-2999	3000-4999	5000-7999	8000-10999	11000-14999	15000-19999	20000-29999	30000-49999	>50000	Corr. Coef. r(xy)**
N*	42	111	135	190	92	96	53	37	30	27	14	19	8	
Secchi-M	0.6	1.2	1.3	1.4	1.4	1.2	1.0	1.0	1.0	1.0	0.9	0.8	0.6	-.64
Chlor a mg/m^3	3	4(15)	6	5(31)	9(19)	14(22)	20(20)	26(21)	26(15)	33	26	38(14)	82	.963
TP mg/m^3	87	44	36	38	35	40	69	49	68	75	63	107	280	.92
SD-TSI	69.9	61.2	59.2	57.0	56.4	57.8	60.8	61.0	60.7	61.0	61.9	64.7	69.3	.59
CH-TSI	40.3	41.5(15)	44.2	45.1(31)	49.7(19)	55.5(22)	55.8(20)	61.3(21)	61.1(15)	62.1	60.9	63.9(14)	70.7	.79
TP-TSI	60.0	50.2	47.6	46.3	47.5	59.1	54.2	52.6	56.7	55.0	57.1	61.1	74.4	.88
Color Pt Units	50	59(34)	52	59(38)	62(24)	29(29)	17(27)	36(25)	23(17)	24	14	15(16)	17	-.64
Turb. JTU	34	19(53)	12	12(100)	9(52)	12(53)	12(34)	12(29)	12(23)	14	13	14	23	.19
Aut. Wgt.	5.0(21)	6.6(26)	7.8(27)	5.7(63)	3.2(33)	3.0(33)	8.1(20)	4.4(9)	7.5(9)	5.7(8)	5.2(2)	4.2(4)	7.2(1)	.14
Filt. Wgt.	1.8(21)	2.1(26)	4.1(27)	2.4(63)	1.3(33)	1.2(33)	2.4(20)	0.6(9)	4.5(9)	1.8(8)	0.3(2)	1.5(4)	2.9(1)	.02
Cell Den. no./ml	156	471	799	1437	2439	3838	6494	8999	12896	17480	24735	38124	71091	-
Biovol. mm^3/m^3	1034	503	695	1056	1624	2278	4105	5008	4725	5387	7803	10616	21973	.991
Shan-Weaver	3.302	3.581	3.646	3.663	3.650	3.764	3.653	3.753	3.795	3.360	3.143	3.201	3.311	-.56
Evenness	0.714	0.721	0.703	0.674	0.657	0.655	0.626	0.629	0.639	0.560	0.537	0.540	0.541	-.78
Pollution Index	33	33	57	59	96	105	196	259	291	316	341	632	1389	.987
Taxa, no. sp.	22	28	33	40	46	51	55	59	60	60	54	59	67	.66
BI-A	3.0	5.5	6.3	7.0	6.5	8.0	9.7	10.1	10.7	8.9	11.6	11.0	9.6	.54
BI-B	7.5	10.8	11.6	11.9	10.5	13.6	16.2	17.3	17.8	14.8	19.0	17.5	15.5	.50
BI-C	1.2	1.3	1.4	1.4	1.5	1.5	1.4	1.1	1.5	1.4	1.6	1.4	1.1	-.30
BI-D	71.6	77.5	85.1	81.0	72.5	78.2	86.8	72.3	73.5	75.8	76.4	76.0	91.1	.45
BI-E	69.0	71.1	77.5	70.2	63.4	69.1	77.2	62.5	64.3	67.8	68.7	63.4	80.1	.26

*If N deviates from values shown by more than 10% then actual N is in parenthesis.

**5% level of significance >.532

1% level of significance >.661.

Table 22

Mean Values or Trophic State Indices
Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

Biovolume mm^3/m^3

Range of Values	10-299	300-599	600-999	1000-1999	2000-2999	3000-4999	5000-7999	8000-10999	11000-14999	15000-19999	20000-29999	>30000	Corr. Coef. r(xy)**
N*	132	150	144	190	67	78	46	20	12	6	7	2	
Secchi-M	1.0	1.2	1.4	1.3	1.3	1.3	0.9	0.8	0.7	0.9	0.7	0.8	-.58
Chlor a mg/m^3	4(11)	5(12)	5	10(11)	16(28)	23(41)	27(24)	47(12)	29(4)	36(3)	69(5)	204(1)	.978
TP mg/m^3	67	42	34	35	37	53	68	99	106	85	460	186	.975
SD-TSI	64.6	59.7	57.5	56.8	57.9	57.9	62.8	63.3	65.2	62.3	67.3	64.0	.46
CH-TSI	42.0(11)	42.8(12)	43.3	50.7(44)	55.3(28)	58.1(41)	62.2(24)	65.2(12)	62.0(4)	63.7(3)	69.8(5)	82.0(1)	.85
TP-TSI	55.6	49.2	45.9	46.6	47.7	51.4	56.7	61.6	62.7	59.8	68.3	71.0	.82
Color Pt Units	65(34)	69(25)	52	19(61)	43(30)	29(43)	38(25)	28(14)	18(4)	23(3)	15(5)	15	-.56
Turb. JTU	26(60)	14(66)	13	16(104)	20(46)	11(60)	12(36)	16(14)	18(7)	13(4)	20	18	.23
Aut. Wgt.	10.8(39)	5.2(28)	4.2(41)	3.7(68)	3.8(23)	5.2(25)	6.8(17)	3.6(5)	6.4(6)	4.2(2)	5.9(2)	-	-.19
Filt. Wgt.	4.4(39)	3.5(28)	1.2(41)	1.3(68)	1.3(23)	1.1(25)	4.2(17)	2.0(5)	1.5(6)	1.5(2)	1.0(2)	-	-.20
Cell Den. no./ml	610	1289	1793	3018	6161	9352	15241	23104	23837	27758	39274	33809	.81
Biovol. mm^3/m^3(x)	175	454	781	1417	2432	3871	6049	9233	13019	17280	23779	55744	-
Shan-Weaver	3.306	3.584	3.546	3.712	3.855	3.894	3.772	3.578	3.547	3.124	3.584	3.102	-.64
Evenness	0.692	0.689	0.653	0.665	0.668	0.664	0.640	0.611	0.604	0.651	0.605	0.528	-.87
Pollution Index	45	55	56	115	135	181	309	522	991	442	1333	2128	.963
Taxa, no. sp.	25	35	40	45	54	57	58	57	59	47	62	56	.38
BI-A	5.1	6.8	6.9	7.4	7.6	8.5	8.8	11.4	13.2	7.8	11.2	6.6	-.001
BI-B	9.8	11.9	11.7	12.9	13.2	14.3	15.3	18.2	21.4	12.3	16.9	11.6	-.02
BI-C	1.3	1.5	1.4	1.4	1.3	1.3	1.4	1.5	1.4	1.0	1.3	0.5	-.91
BI-D	79.9	84.0	82.7	79.6	74.6	67.8	75.3	86.7	60.1	63.9	95.5	50.0	-.80
BI-E	74.2	75.6	74.5	70.3	61.2	56.9	64.5	79.8	52.8	61.0	88.7	49.8	-.63

*If N deviates from values shown by more than 10% then actual N is in parenthesis,
**5% level of significance >.553
1% level of significance >.684.

Table 23

Mean Values of Trophic State Indices
Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

Shannon-Weaver Diversity Index

Range of Values	.50-1.999	2.0-2.999	3.0-3.999	4.0-4.999	>5.0	Corr. Coef. r(xy)**
N*	37	130	393	265	27	
Secchi-M	1.4	1.4	1.2	1.0	1.1	-.89
Chlor a mg/m^3	11(14)	12(43)	14(47)	26(88)	22(20)	.86
TP mg/m^3	31.4	45.1	43.9	64.0	40.0	.52
SD-TSI	58.1	57.3	59.1	61.8	58.0	.41
CH-TSI	52.5(14)	50.7(43)	51.1(47)	56.0(88)	60.0(20)	.77
TP-TSI	46.2	48.6	48.6	54.3	51.2	.82
Color Pt Units	54(25)	49(49)	55(78)	25(107)	12(19)	-.85
Turb. JTU	6(29)	10(84)	12(17[illegible]	19(161)	13(24)	.80
Aut. Wgt.	3.2(8)	4.5(32)	5.1(120)	6.6(91)	3.8(5)	.45
Filt. Wgt.	1.3(8)	2.7(32)	1.7(120)	2.6(91)	1.4(5)	.08
Cell Den. no./ml	9910	7245	3425	4999	7786	-.47
Biovol. mm^3/m^3	2889	2529	1729	2723	3724	.35
Shan-Weaver (x)	1.521	2.611	3.541	4.391	5.120	–
Evenness	0.341	0.527	0.672	0.762	0.809	.987
Pollution Index	92	187	95	177	235	.69
Taxa, no. sp.	27	33	38	53	78	.92
BI-A	5.5	6.0	6.5	9.0	9.2	.94
BI-B	9.6	10.5	11.5	15.6	15.2	.92
BI-C	1.0	1.2	1.5	1.4	1.3	.71
BI-D	54.7	72.2	81.6	82.8	78.6	.84
BI-E	50.5	65.3	73.9	72.0	57.7	.41

*If N deviates from values shown by more than 10% then actual N is in parenthesis.
**5% level of significance >.811
1% level of significance >.917.

Table 24

Mean Values of Trophic State Indices
Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

Evenness Diversity Index

Range of Values	.013-.399	.400-.499	.500-.599	.600-.699	.700-.799	.800-.899	>.900	Corr. Coef. r(xy)**
N*	39	50	125	226	333	78	3	
Secchi-M	1.3	1.3	1.3	1.3	1.1	0.9	0.4	-.80
Chlor a mg/m^3	11(15)	17(19)	17(30)	19(35)	25(82)	12(30)	3	-.22
TP mg/m^3	38	43	42	45	56	54	168	.68
SD-TSI	58.4	58.3	57.0	58.5	60.6	63.3	78.3	.72
CH-TSI	52.2(15)	55.4(19)	53.7(30)	51.0(35)	56.6(82)	51.3(30)	35.5(2)	-.56
TP-TSI	49.2	48.3	47.8	48.1	52.0	54.2	72.3	.72
Color Pt Units	30(22)	49(25)	41(35)	50(52)	37(109)	27(35)	32(2)	-.27
Turb. JTU	8(26)	9(36)	9(69)	12(101)	15(193)	25(49)	57(2)	.77
Aut. Wgt.	4.3(6)	2.5(13)	4.3(42)	5.6(68)	5.8(100)	7.3(26)	6.6(1)	.82
Filt. Wgt.	1.7(6)	1.7(13)	2.0(42)	1.8(68)	2.5(100)	2.7(26)	1.8(1)	.53
Cell Den. no./ml	12030	13081	7061	3608	3670	2073	933	-.94
Biovol. mm^3/m^3	3090	4378	2879	2108	1944	1450	853	-.86
Shan-Weaver	1.545	2.408	3.011	3.557	4.108	4.466	4.157	.93
Evenness (x)	0.299	0.454	0.558	0.657	0.750	0.825	0.927	-
Pollution Index	104	137	134	119	135	93	80	-.46
Taxa, no. sp.	33	39	41	41	45	44	29	.08
BI-A	6.9	6.6	6.2	7.1	8.0	7.0	5.3	-.19
BI-B	12.0	11.5	10.6	11.9	13.9	13.2	11.2	.27
BI-C	1.1	1.2	1.4	1.5	1.4	1.4	0.6	-.22
BI-D	66.0	70.4	70.6	81.5	83.5	79.3	67.4	.42
BI-E	57.5	66.2	64.7	73.1	73.0	68.2	78.0	.88

*If N deviates from values shown by more than 10% then actual N is in parenthesis.
**5% level of significance >.707
1% level of significance >.834.

.70-.74 range. Shannon-Weaver is well correlated with Evenness but Shannon-Weaver is poorly correlated with cell number and cell volume in contrast to the good negative correlations of Evenness. Shannon-Weaver has good correlation with taxa and the biological indices A, B and D whereas Evenness is poorly correlated with these except for E.

Pollution Index

Due to the wide range of values for the Pollution Index, from less than 1 to over 3,000, 14 subsets of values were examined for the relationship of this index and the other trophic state indices (Table 25). The highlights are the unusually high correlations with chlorophyll a, total phosphorus, very significant correlations with chlorophyll-TSI and total phosphorus-TSI. Very strong correlations with cell density and biovolume are evident and somewhat poorer correlations but significant with the biological indices C, D and E.

The relationship of these subsets of values for the Pollution Index to other nutrient ranges and other measures of trophic level are presented in Table 26. Strong significant correlations >0.9, when 170 level of significance is >.641, are noted for Kjel-N, all the phosphorus fractions, conductivity, chlorophyll a-Turner and productivity. A good negative correlation is shown for the rates of inorganic nitrogen/soluble phosphorus and a marginal correlation but significant at the 5% level for NO_2+NO_3-N. The degree response of the characteristic population used to determine the Pollution Index appears to represent a sensitive indicator of changing quality related to nutrient levels.

Taxa

Using as a trophic state indicator the changing number of individual species found in a particular water sample, this variable was examined in relationship to the other trophic state indices (Table 28). The correlations were very good with Secchi depth, chlorophyll a, total phosphorus, the direct determinations of cell quantity, density and volume, as well as with the Shannon-Weaver, Evenness indices and the Pollution Index. Except for BI-B it was only marginally if at all correlated with the other biological indices.

Table 25

Mean Values of Trophic State Indices Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

PI (Pollution Index)

Range of Values	0-0.9	1-9	10-19	20-39	40-59	60-79	80-99	100-149	150-199	200-299	300-499	500-999	1000-2999	>3000	Corr. Coef. r(xy)**
N*	62	69	78	129	118	68	42	87	63	45	42	24	12	5	
Secchi-M	1.6	1.6	1.5	1.1	1.1	1.1	1.1	1.1	1.1	0.9	1.0	0.8	0.8	0.7	-.59
Chlor a mg/m³	6(23)	4(17)	5(18)	7(24)	10(15)	11(13)	15(10)	19(16)	21(21)	23(19)	36(15)	50(14)	61(6)	166(2)	.989
TP mg/m³	30	33	38	48	48	41	39	38	53	46	86	116	134	351	.991
SD-TSI	57.2	55.6	57.1	60.7	60.5	60.0	59.4	58.8	59.3	61.4	61.7	65.5	65.0	66.6	.73
CH-TSI	45.2(23)	43.5(17)	42.7(18)	48.5(24)	49.7(15)	53.1(13)	55.6(10)	58.3(16)	59.4(21)	59.2(19)	64.0(15)	67.1(14)	70.0(6)	81.0(2)	.80
TP-TSI	44.5	45.6	46.7	49.9	50.5	50.1	49.7	49.2	53.2	51.4	56.8	63.3	67.3	75.2	.88
Color Pt Units	69(36)	44(27)	33(21)	33(36)	26(20)	17(19)	13(11)	39(24)	57(25)	15(21)	46(18)	27(14)	96(6)	15(2)	-.07
Turb. JTU	7(47)	10(47)	15(39)	17(64)	21(56)	13(27)	14(19)	11(42)	11(39)	16(30)	12(29)	16(20)	16	15	.17
Aut. Wgt.	1.1(13)	6.0(16)	4.6(15)	6.2(38)	6.3(45)	4.7(21)	5.1(9)	3.1(29)	8.3(20)	4.7(14)	3.7(19)	11.2(8)	10.2(6)	3.8(3)	.05
Filt. Wgt.	0.6(13)	1.8(16)	2.7(15)	2.3(38)	1.8(45)	2,5(21)	3.3(9)	1.2(29)	4,1(20)	1.2(4)	1.1(19)	2.7(8)	7.1(6)	1.8(3)	.15
Cell Den. no./ml	1720	1501	1816	1865	2233	3027	3734	3767	8477	11108	11390	19266	38124	38331***	.86(.993)
Biovol. mm³/m³	1280	1037	999	1076	1307	1308	1739	2152	3441	3744	5486	7396	10538	25307	.991
Shan-Weaver	2.660	3.385	3.438	3.649	3.753	3.744	3.760	3.781	3.793	3.833	3.939	3.879	3.447	3.753	.14
Evenness	0.609	0.663	0.654	0.679	0.686	0.672	0.669	0.688	0.659	0.664	0.665	0.673	0.577	0.629	-.45
Pollution Index(x)	0	6	15	29	49	69	88	121	174	245	381	706	1432	4180	-
Taxa, no. sp.	20	32	35	39	43	45	48	43	54	54	60	54	60	60	.52
BI-A	2.9	4.5	5.1	6.5	6.6	8.3	9.0	8.7	9.0	9.5	11.3	12.1	7.8	10.1	.36
BI-B	5.4	8.0	9.5	11.9	11.7	14.7	15.8	14.8	15.2	15.9	18.3	18.9	11.7	15.9	.26
BI-C	1.0	1.1	1.3	1.5	1.4	1.4	1.6	1.6	1.5	1.2	1.9	1.4	1.1	2.3	.64
BI-D	53.6	71.0	79.7	80.0	80.2	80.5	83.3	84.6	81.7	85.1	80.4	90.7	92.7	98.3	.61
BI-E	48.7	62.2	70.9	71.4	72.1	71.8	74.5	75.8	68.0	76.4	70.2	80.3	85.2	97.6	.77

*If N deviates from values shown by more than 10% then actual N is in parenthesis.
**5% level of significance >.514
1% level of significance >.641.
***Value not used in calculating r in ( ).

Table 26

Mean Values of Physical, Chemical and Biological Parameters
of Lake Samples Collected for Trophic Analysis
Within Value Range of Trophic Index

Pollution Index

Range of Values	0-0.9	1-9	10-19	20-39	40-59	60-79	80-99	100-149	150-199	200-299	300-499	500-999	1000-2999	>3000	Corr. Coef. r(xy)
N*	62	69	78	129	118	68	42	97	63	45	42	24	12	5	
Temp. °C	19.2	18.7	19.5	17.9	19.5	19.2	19.6	19.0	21.0	20.7	21.5	16.8	25.4	20.2	.27
Secchi-Ft.	5.2	5.2	4.9	3.8	3.7	3.5	3.6	3.7	3.7	3.1	3.2	2.6	2.8	2.3	-.61
Secchi-M	1.6	1.6	1.5	1.1	1.1	1.1	1.1	1.1	1.1	1.0	1.0	0.8	0.8	0.7	-.61
NH_3-N mg/m^3	44	50	69	76	70	77	66	69	67	63	84	172	100	102	.40
NO_2NO_3-N mg/m^3	100	127	148	194	179	178	150	159	147	95	101	125	50	80	-.56
Kjel-N mg/m^3	257	250	262	280	302	273	298	271	359	352	528	565	762	940	.90
Inorg-N mg/m^3	144	177	217	271	249	255	216	228	214	158	185	297	150	182	-.23
Org-N mg/m^3	213	200	193	203	232	195	232	203	292	289	443	393	662	838	.92
Total N mg/m^3	357	376	410	474	481	451	448	429	506	446	631	690	812	1020	.91
PO_4-P mg/m^3	6.6	10.9	13.4	17.1	13.6	15.1	13.1	12.1	16.2	12.6	29.0	39.0	34.0	77.0	.952
Total Sol P mg/m^3	11.8	18.1	21.5	27.3	20.5	22.7	21.4	19.3	28.3	18.2	42.7	64.4	56.4	182.0	.980
Sol Org P mg/m^3	5.1	7.1	8.6	10.3	7.2	7.8	8.3	7.3	11.8	5.6	13.7	25.3	15.7	105.0	.965
Part-P	18.4	14.8	17.3	21.7	28.4	18.9	18.3	19.5	25.8	28.0	43.3	52.0	77.4	168.6	.992
Total P mg/m^3	30.2	32.9	38.3	48.4	49.2	40.6	38.9	38.2	52.7	46.3	85.9	116.4	133.8	350.6	.991
TN/TP	18.2	17.9	18.6	16.0	15.9	16.8	15.5	15.7	15.6	14.9	14.7	9.1	9.1	11.0	-.63
Inorg N/Sol P mg/m^3	13.7	14.8	14.5	15.4	16.2	20.4	15.5	17.3	12.7	13.4	12.6	11.5	3.6	2.9	-.82
Alkalinity mg/1	9.0(47)	16.6(45)	17.8(39)	19.4(58)	22.3(51)	20.7(21)	25.7(19)	20.7(35)	21.8(31)	22.2(28)	24.2(24)	22.9(15)	24.9	27.0	.51
Cond μmhos/cm^3	57(46)	86(46)	68(39)	77(61)	87.4(55)	99.7(26)	18.8(22)	113.4(44)	95.4(41)	113.9(29)	168.1(20)	241.0	241.0	347.2	.93
Cell Density	1720	1501	1816	1865	2233	3027	3734	3767	8478	11108	11390	19266	38124	38331	.86
Biovolume mm^3/m^3	1280	1037	999	1076	1307	1308	1739	2152	3441	3744	5486	7396	10538	25707	.991
Ln Cell Density	6.6820	6.7977	6.8479	6.9849	7.2648	7.4462	7.7511	7.6281	8.5289	8.6812	8.8152	9.5436	9.2060	9.9092	.70
Ln Biovol	6.2704	6.4873	6.4060	6.3816	6.6793	6.7527	6.9853	7.0719	7.6877	7.7247	8.2724	8.6078	8.7921	9.4572	.78
Chlor *a* Turner Units	20	21	21	25	26	29	28	32	46	51	70	84	105	181	.95
Prod mg C/m^3/hr	11.5	22.8	17.3	22.0	26.1	39.4	43.4	44.9	55.1	79.8	97.5(28)	118.3	145.1	263	.94
Pollution Index (x)	0	6	15	29	49	69	88	121	174	245	381	706	1432	4180	-

*If N deviates from values shown by more than 10% then actual N is in parenthesis.
**5% level of significance >.514
1% level of significance >.641.

Table 27

Mean Values of Trophic State Indices Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

Taxa (species)

Range of Values	1-19	20-29	30-39	40-49	50-59	60-69	70-79	80-98	Corr. Coef. r(xy)**
N*	60	159	192	162	135	83	40	23	
Secchi-M	1.2	1.4	1.3	1.2	1.0	1.1	1.0	0.9	-.84
Chlor a mg/m^3	7	6(28)	10(26)	15(31)	20(33)	24(35)	31(26)	42(18)	.97
TP mg/m^3	55	39	47	39	55	63	73	89	.81
SD-TSI	61.9	58.7	58.9	58.9	60.2	60.2	61.1	61.8	.37
CH-TSI	46.1	45.4(28)	47.5(26)	53.0(31)	54.5(33)	58.5(35)	61.5(26)	64.2(18)	.981
TP-TSI	51.0	47.8	48.3	48.6	53.3	54.2	55.5	54.5	.79
Color Pt Units	83	42(34)	89(44)	24(48)	19(38)	13(38)	16(28)	14(19)	-.78
Turb. JTU	3.6(15)	5.9(31)	7.7(59)	4.3(65)	5.3(50)	4.2(21)	5.9(10)	2.2(5)	.41
Aut. Wgt.	1.6(15)	2.9(31)	3.4(59)	1.6(65)	1.8(50)	1.5(21)	1.1(10)	0.8(5)	-.34
Filt. Wgt.	1.6	3.1(23)	3.2(44)	1.3(43)	1.9(37)	1.8(18)	1.2(8)	1.0(4)	-.66
Cell Den. no./ml	972	1238	2058	6242	6428	9248	12740	17445	.969
Biovol. mm^3/m^3	495	1227	1279	2000	3038	3585	6055	8452	.94
Shan-Weaver	2.460	3.230	3.509	3.640	3.896	4.190	4.467	4.901	.982
Evenness	0.611	0.669	0.666	0.651	0.664	0.690	0.711	0.759	.90
Pollution Index	15	89	91	112	181	285	314	552	.94
Taxa, no. sp.(x)	14	25	34	44	54	64	74	86	-
BI-A	2.4	5.3	6.5	8.1	8.5	9.8	11.7	8.6	.54
BI-B	5.0	9.7	11.6	14.1	14.6	16.1	19.4	14.4	.85
BI-C	1.0	1.2	1.5	1.5	1.4	1.5	1.4	1.2	.35
BI-D	57.3	77.7	85.1	80.7	79.4	76.5	82.6	85.4	.63
BI-E	53.3	70.2	79.3	70.7	69.0	62.9	72.6	66.9	.21

*If N deviates from values shown by more than 10% then actual N is in parenthesis.
**5% level of significance >.666
1% level of significance >.798.

Biological Indices, Phytoplankton Quotients

Each of these indices subdivided into 9 or 10 subsets of values describe changes in population composition based on the relative numbers of specific classes of planktonic algae. The quotient of percentage appear to be biased to trophic levels, ultra oligotrophic, which are seldom observed in the waters of this region. They would also appear to lack sensitivity to changes in nutrient level even though they show good step relationships, in some instances over the entire scale of changing quality as indicated by the other indices (Tables 28-32). To summarize the key relationships, Table 33 has been prepared which examines the magnitude of correlation determined for each of these five, with each other and with chlorophyll a, total phosphorus, cell density, biovolume and the Pollution index.

It would appear that the biological indices BI-A and BI-B are well related to chlorophyll a, total phosphorus, cell density, biovolume and the Pollution Index and to each other. The latter might be expected since their basic relationships are quite similar, in both instances the number of Desmidiaceae being the denominator. The BI-C quotient, one based on differences in morphology of two general classes appears to have little or no correlations with chlorophyll a, total phosphorus, cell density and biovolume but a reasonably good one with the Pollution index. Both good and excellent BI-D, based on cell density and BI-E, based on cell volume, show good and excellent correlation with chlorophyll a. Only BI-E (volume) has a good correlation with total phosphorus and both have negative correlations to cell density and biovolume but not significant. Both correlate positively to the Pollution Index but BI-E has the strongest correlation. The cross correlations of the indices with each other confirm the similarity of BI-A and BI-B by their very high correlation and their somewhat lesser degree of correlation with C, D and E. D and E show reasonably good cross correlation with the other indices whereas C has the lowest correlations with A, B and D and somewhat stronger with E.

The consistent pattern of strong correlations by trophic index BI-B shown in Table 33 suggested examination of its relationships to other nutrients and trophic measures (Table 34). Several features are unique and different from the correlation patterns noted previously. All the nitrogen parameters are positively correlated and significant in most instances at the 1% level. All phosphorus relationships are positively correlated and at even higher levels than the nitrogen components. One exception to previous analysis of this type is the non-correlation with conductivity.

Table 28

Mean Values of Trophic State Indices
Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

BI-A (Biological Index, $\frac{\text{Species - Chlorococcales}}{\text{Species - Desmidiaceae}}$)

Range of Values	0.0-0.9	1.0-1.9	2.0-2.9	3.0-3.9	4.0-5.9	6.0-7.9	8.0-9.9	10.0-14.9	15.0-19.9	>20	Corr. Coef. r(xy)**
N*	14	41	87	99	182	131	93	122	56	29	
Secchi-M	0.9	1.4	1.6	1.3	1.2	1.1	1.2	1.0	1.0	0.9	-.57
Chlor a mg/m^3	13(6)	3(12)	7(18)	6(16)	13(34)	19(42)	14(25)	35(32)	34(19)	43(9)	.92
TP mg/m^3	65	47	25	45	42	43	49	70	59	114	.78
SD-TSI	63.2	59.2	55.3	58.3	59.4	50.0	59.5	61.5	61.4	63.6	.55
CH-TSI	53.8(6)	40.5(12)	45.1(18)	46.4(16)	52.6(34)	55.6(42)	51.2(25)	61.5(32)	62.1(19)	64.1(9)	.82
TP-TSI	50.7	49.2	43.3	47.8	48.8	50.4	51.7	54.7	52.7	62.2	.85
Color Pt Units	84	61(17)	44(24)	67(20)	42(44)	30(43)	28(27)	26(49)	34(28)	24(14)	-.72
Turb. JTU	22	16(30)	7(50)	11(49)	13(99)	15(75)	13(50)	20(59)	14(33)	14(17)	.01
Aut. Wgt.	1.4(4)	8.8(9)	4.1(21)	5.7(41)	3.0(49)	5.8(29)	4.4(29)	8.3(44)	6.1(19)	6.6(11)	.37
Filt. Wgt.	0.1(4)	3.2(9)	1.3(21)	2.6(41)	1.6(49)	2.1(29)	1.8(29)	3.1(44)	1.9(19)	2.4(11)	.30
Cell Den. no./ml	771	1736	2064	3646	3972	6718	4640	6753	8653	8360	.90
Biovol. mm^3/m^3	1820	1229	1876	1769	1466	2745	2398	3227	2826	4244	.91
Shan-Weaver	2.348	3.157	3.355	3.462	3.605	3.712	3.715	3.864	3.820	4.121	.77
Evenness	0.612	0.650	0.648	0.655	0.668	0.674	0.666	0.681	0.666	0.708	.82
Pollution Index	12	36	34	74	98	156	131	179	205	357	.975
Taxa, no. sp.	14	27	34	37	42	44	46	49	52	55	.83
BI-A (x)	0.3	1.4	2.4	3.3	4.8	6.7	8.6	11.6	16.7	23.8	-
BI-B	1.1	3.4	4.6	5.9	8.7	11.8	15.2	20.1	27.4	37.5	.999
BI-C	0.2	1.1	1.2	1.3	1.4	1.3	1.5	1.5	1.7	1.8	.74
BI-D	13.7	57.3	67.5	73.9	81.1	82.8	88.0	87.3	86.2	87.7	.61
BI-E	13.5	48.7	60.1	65.8	70.7	71.8	80.4	80.0	77.8	77.5	.63

*If N deviates from values shown by more than 10% then actual N is in parenthesis.
**5% level of significance >.602
1% level of significance >.735.

Table 29

Mean Values of Trophic State Indices
Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

$$\text{BI-B (Biological Index, } \frac{\text{Species} + \text{Cyanophycae} + \text{Chlorococcales} + \text{Centrales} + \text{Eugleniaceae}}{\text{Desmidiaceae}}\text{)}$$

Range of Values	0.0-0.9	1.0-2.5	2.6-3.9	4.0-5.9	6.0-7.9	8.0-9.9	10.0-14.9	15.0-19.9	20.0-29.9	>30.0	Corr. Coef. r(xy)**
N*	10	18	42	114	113	99	190	116	111	41	
Secchi-M	0.8	1.8	2.0	1.5	1.2	1.3	1.1	0.9	1.0	0.9	-.53
Chlor $\underline{a}$ mg/m^3	18(3)	6(9)	4(10)	10(17)	7(24)	19(26)	16(48)	32(31)	24(31)	39(14)	.85
TP mg/m^3	23	29	32	38	41	47	41	75	61	83	.93
SD-TSI	63.2	54.8	52.0	56.3	59.2	58.3	60.1	63.0	61.9	63.2	.59
CH-TSI	59.0(3)	43.3(9)	41.6(10)	46.4(17)	48.2(24)	54.2(26)	54.2(48)	58.7(31)	59.1(31)	62.8(14)	.71
TP-TSI	45.2	45.4	42.4	45.0	49.1	48.6	50.3	56.6	52.6	59.7	.85
Color Pt Units	107	63(10)	84(16)	71(23)	46(31)	25(27)	20(54)	31(39)	31(49)	21(21)	-.70
Turb. JTU	4	8(15)	11(32)	9(63)	12(62)	14(62)	12(94)	25(56)	17(59)	15(23)	.62
Aut. Wgt.	1.4(4)	5.4(3)	2.2(9)	6.4(34)	4.4(42)	3.0(26)	4.9(47)	8.5(40)	5.8(36)	6.5(15)	.56
Filt. Wgt.	0.1(4)	2.1(3)	1.2(9)	2.4(34)	2.0(42)	1.0(26)	2.7(47)	3.2(40)	1.4(36)	2.3(15)	.36
Cell Den. no./ml	862	2851	1872	3082	4045	5648	4903	6236	5662	10201	.93
Biovol. mm^3/m^3	937	2665	2259	1772	1507	2047	2250	2920	2419	4312	.81
Shan-Weaver	2.213	2.725	3.103	3.400	3.561	3.680	3.691	3.827	3.879	3.852	.71
Evenness	0.602	0.570	0.623	0.649	0.664	0.673	0.676	0.683	0.687	0.662	.60
Pollution Index	0	47	31	102	135	183	135	193	144	313	.88
Taxa, no. sp.	12	26	30	37	40	44	43	47	49	54	.81
BI-A	0.3	1.2	2.1	2.9	3.9	5.0	6.7	9.6	13.8	21.7	.999
BI-B (x)	0.3	1.8	3.2	4.8	6.7	8.7	12.0	17.2	23.8	36.7	-
BI-C	0.1	0.5	0.9	1.4	1.2	1.4	1.4	1.5	1.7	1.7	.74
BI-D	0.4	27.1	53.3	77.0	75.5	80.7	84.4	87.8	87.8	86.1	.63
BI-E	0.2	13.5	44.1	70.1	67.2	66.4	75.8	79.8	80.7	77.1	.65

*If N deviates from values shown by more than 10% then actual N is in parenthesis.
**5% level of significance >.602
1% level of significance >.755.

Table 30

Mean Values of Trophic State Indices
Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

BI-C (Biological Index, $\frac{\text{Species - Centrales}}{\text{Species - Pennales}}$)

Range of Values N*	0.0-0.2 50	0.3-0.5 57	0.6-0.8 105	0.9-1.1 184	1.2-1.4 138	1.5-1.7 109	1.8-2.1 110	2.2-2.9 45	>3.0 29	Corr. Coef. r(xy) **
Secchi-M	1.0	1.6	1.2	1.3	1.0	1.1	1.2	1.0	1.0	-.43
Chlor a mg/m³	11(19)	9(21)	11(23)	27(53)	21(35)	21.(25)	19.9(20)	11.5(8)	18(4)	.23
TP mg/m³	38	57	48	53	40	49	57	52	53	.34
SD-TSI	62.1	57.6	59.9	58.7	60.5	59.4	59.1	61.7	61.4	.35
CH-TSI	50.3(19)	44.3(21)	50.2(23)	55.8(53)	57.3(35)	57.6(25)	55.1(20)	53.4(8)	55.2(4)	.45
TP-TSI	50.1	49.0	50.0	49.5	49.6	51.7(108)	51.1	53.0	51.7	.56
Color Pt Units	76(32)	32(26)	22(41)	37(67)	21(41)	18(30)	72(25)	19(8)	58(5)	.04
Turb. JTU	6(35)	17(48)	18(70)	13(116)	15(56)	15(50)	12(57)	15(13)	11(11)	-.09
Aut. Wgt.	8.1(17)	2.5(13)	7.7(37)	4.8(57)	4.9(39)	5.9(35)	3.7(19)	4.1(8)	6.9(13)	.02
Filt. Wgt.	2.2(17)	1.5(13)	3.5(37)	2.0(57)	1.3(39)	2.3(35)	1.5(19)	0.6(8)	3.5(13)	.26
Cell Den. no./ml	2949	438	4711	5604	6643		3713	3095	4817	.12
Biovol. mm³/m³	3099	1849	1782	2742	2572	2276	1532	2187	2117	-.26
Shan-Weaver	2.688	3.395	3.637	3.736	3.728	3.670	3.639	3.927	3.597	.44
Evenness	0.575	0.670	0.664	0.6797	0.667	0.666	0.672	0.703	0.662	.37
Pollution Index	47	111	112	157	149	158	166	121	260	.87
Taxa, no. sp.	25	34	44	45	46	45	41	47	41	.39
BI-A	3.6	5.2	7.4	7.0	7.7	7.9	7.2	10.7	8.2	.66
BI-B	5.7	8.5	12.5	11.8	13.6	14.2	12.9	19.3	14.7	.64
BI-C (x)	0.0	0.4	0.7	1.0	1.3	1.6	1.9	2.5	5.0	-
BI-D	2.7	54.1	75.7	80.6	89.0	90.0	90.3	94.5	95.4	.63
BI-E	2.5	39.0	63.1	69.1	80.6	81.3	84.4	89.5	95.8	.73

*If N deviates from values shown by more than 10% then actual N is in parenthesis.
**5% level of significance >.632
1% level of significance >.765.

Table 31

Mean Values of Trophic State Indices
Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

BI-D (Biological Index, $\frac{\text{Centrales}}{\text{Centrales + Araphidineae}}$ = % of C + A by Cell Density

Range of Values	0.0-0.9	1.0-9.9	10.0-29.9	30.0-49.9	50.0-59.9	60.0-69.9	70.0-79.9	80.0-89.9	90.0-99.9	>100.0	Corr. Coef. r(xy)**
N*	48	12	28	35	45	34	48	113	403	88	
Secchi-M	1.1	1.9	1.5	1.6	1.3	1.5	1.5	1.2	1.0	1.2	-.48
Chlor a mg/m^3	10(20)	7(7)	11(15)	13(10)	13(17)	10(9)	11(13)	15(29)	29(81)	24(12) .74	.74
TP mg/m^3	38	21	40	22	35	22	29	41	58	77 .57	.57
SD-TSI	61.5	56.1	55.5	54.1	58.8	54.8	55.7	59.4	61.1	59.9	.24
CH-TSI	49.4(20)	46.4(7)	52.5(15)	54.2(10)	53.0(17)	48.0(9)	50.5(13)	52.3(29)	57.7(81)	55.9(12)	.62
TP-TSI	49.9	41.5	47.2	42.0	47.3	41.6	43.1	49.1	52.9	54.4	.44
Color Pt Units	75(33)	34(7)	18(18)	19(8)	26(20)	16(13)	32(17)	18(33)	41(110)	72(21)	-.02
Turb. JTU	6(35)	7(8)	8	7(22)	13(29)	8(23)	12(28)	19	17(207)	10(42)	.72
Aut. Wgt.	8.4(16)	3.6(4)	3.0(5)	2.6(13)	1.6(9)	5.3(8)	2.8(17)	3.4(31)	6.6(122)	6.0(31)	.01
Filt. Wgt.	2.4(16)	2.8(4)	0.1(5)	1.3(13)	0.7(9)	3.1(8)	1.3(17)	1.7(31)	2.3(122)	3.1(31)	.20
Cell Den. no./ml	2786	4482	9759	6293	5274	3957	3709	4250	5248	4339	-.19
Biovol. mm^3/m^3	3294	2401	3075	3250	1801	1482	1544	2209	2289	1983	-.64
Shan-Weaver	2.594	3.251	3.249	3.868	3.759	3.719	3.759	4.019	3.655	3.372	.65
Evenness	0.562	0.620	0.571	0.682	0.685	0.690	0.680	0.722	0.671	0.637	.69
Pollution Index	46	49	93	124	94	68	53	120	190	173	.70
Taxa, no. sp.	23	39	50	50	45	42	45	47	43	39	.35
BI-A	3.3	5.6	5.6	5.2	6.9	6.2	6.6	7.7	7.9	8.3	.90
BI-B	5.2	11.4	9.5	8.3	12.1	10.1	11.1	13.4	14.1	13.7	.78
BI-C	0.0	0.5	0.9	1.0	1.0	1.2	1.1	1.3	1.5	2.4	.87
BI-D (x)	0.0	5.2	18.9	40.6	54.2	65.4	75.0	85.6	96.3	100.0	-
BI-E	0.0	5.0	11.9	17.1	40.6	49.9	57.0	73.1	88.6	100.0	.97

*If N deviates from values shown by more than 10% then actual N is in parenthesis.
**5% level of significance >.602
1% level of significance >.735.

Table 32

Mean Values of Trophic State Indices
Derived from Lake Samples Collected for Trophic Analysis

Arranged Within Value Ranges of Given Index

BI-E (Biological Index, $\frac{\text{Centrales}}{\text{Centrales + Araphidineae}}$ = % C+A by Cell Volume

Range of Values	0.0-0.9	1.0-9.9	10.0-29.9	30.0-49.9	50.0-59.9	60.0-69.9	70.0-79.9	80.0-89.9	90.0-99.9	>100.0	Corr. Coef. r(xy)**
N*	54	39	57	58	37	56	72	122	268	91	
Secchi-M	1.2	1.7	1.6	1.5	1.4	1.3	1.2	1.1	1.0	1.2	-.70
Chlor a mg/m^3	9(22)	11(16)	9(21)	14(22)	20(8)	19(18)	22(19)	25(29)	27(46)	24(12)	.964
TP mg/m^3	38	30	28	35	41	44	51	53	55	74	.87
SD-TSI	61.8	54.1	54.8	55.8	57.5	58.6	59.3	60.7	61.9	59.3	.54
CH-TSI	49.1(22)	51.6(16)	49.1(21)	53.2(22)	55.3(8)	56.2(18)	55.4(19)	56.9(29)	55.6(46)	55.9(12)	.90
TP-TSI	49.9	44.8	43.6	46.3	49.8	48.5	51.3	52.3	51.8	53.2	.78
Color Pt Units	71(35)	25(18)	14(21)	17(22)	23(12)	31(17)	14(25)	36(46)	51(64)	71(20)	.18
Turb. JTU	6(37)	5(30)	10(41)	10(44)	11(25)	13(33)	17(40)	17(69)	20(115)	10(42)	.78
Aut. Wgt.	8.1(18)	1.8(11)	3.9(14)	5.8(11)	5.0(12)	6.7(11)	3.3(20)	5.0(45)	6.1(79)	5.8(35)	.13
Filt. Wgt.	2.7(18)	1.3(11)	1.6(14)	2.1(11)	4.3(12)	0.9(11)	0.9(20)	1.4(45)	2.5(79)	3.1(35)	.08
Cell Den. no./ml	2936	6848	4770	3960	4403	5141	5952	6551	4124	4208	-.06
Biovol. mm^3/m^3	3295	2645	2430	1609	1656	2445	2512	2414	2133	1986	-.48
Shan-Weaver	2.701	3.494	3.539	3.984	4.080	4.053	3.821	3.665	3.600	3.404	.40
Evenness	0.572	0.631	0.639	0.719	0.729	0.702	0.691	0.662	0.673	0.643	.46
Pollution Index	50	84	93	92	154	134	104	200	178	162	.85
Taxa, no. sp.	26	46.9	44.8	47.4	49.0	53.0	46.5	45.1	39.5	38.3	.16
BI-A	3.6	5.4	6.3	5.9	8.6	8.6	7.1	7.6	7.9	8.2	.81
BI-B	5.9	9.4	10.4	9.8	14.2	14.6	12.4	13.4	14.2	13.7	.85
BI-C	0.1	0.9	1.0	1.1	1.0	1.3	1.3	1.4	1.6	2.4	.91
BI-D	1.4	29.3	47.6	69.3	78.6	81.3	87.8	90.9	95.8	99.3	.95
BI-E (x)	0.0	4.9	19.1	40.1	55.0	64.5	76.0	85.3	92.2	100.0	-

*If N deviates from values shown by more than 10% then actual N is in parenthesis.
**5% level of significance >.602
1% level of significance >.735.

Table 33

Relationship of Biological Indices - Phytoplankton Quotients and Associated Trophic Indices

	Correlation Coefficients(r)				
	BI-A	BI-B	BI-C	BI-D	BI-E
Chlor a	.92	.85	.23	.74	.964
Total-Phosphorus	.78	.93	.34	.57	.87
Cell Density	.90	.93	.12	-.19	-.06
Biovolume	.91	.81	-.26	-.64	-.48
Pollution Index	.975	.88	.87	.70	.85
BI-A	-	.999	.66	.90	.81
BI-B	.999	-	.64	.78	.85
BI-C	.74	.74	-	.87	.91
BI-D	.61	.63	.63	-	.95
BI-E	.63	.65	.73	.97	-

5% level of significance >.632
1% level of significance >.765

Table 34

Mean Values of Physical, Chemical and Biological Parameters
of Lake Samples Collected for Trophic Analysis
Within Value Range of Trophic Index

Phytoplankton Quotient (BI-B)

Range of Values	0.0-0.9	1.0-2.5	2.6-3.9	4.0-5.0	6.0-7.0	8.0-9.0	10.0-14.0	15.0-19.0	20.0-29.0	≥30	Corr. Coef. r(xy)
N*	10	18	42	114	113	99	190	116	111	41	
Temp.°C	18.8	23.8	23.6	21.4	19.2	19.4	18.5	17.2	18.2	21.7	-.22
Secchi-Ft.	2.6	5.9	6.5	5.0	3.9	4.4	3.6	3.0	3.1	2.8	-.56
Secchi-M	0.8	1.8	2.0	1.5	1.2	1.3	1.1	0.9	1.0	0.8	-.58
NH_3-N mg/m^3	42	52	48	53	64	60	63	103	97	89	.83
NO_2NO_3-N mg/m^3	37	75	78	112	153	143	168	190	165	168	.71
Kjel-N mg/m^3	327	279	263	298	285	307	303	364	332	435	.86
Inorg N mg/m^3	79	128	126	164	217	204	230	293	262	257	.78
Org N mg/m^3	286	227	215	246	221	247	241	260	235	347	.65
Total N mg/m^3	364	350	341	410	438	452	471	554	497	604	.92
PO_4-P mg/m^3	5.7	6.8	8.1	14.8	11.7	17.3	12.9	20.2	20.5	24.8	.90
Total Sol P mg/m^3	11.0	15.3	15.3	22.4	18.5	24.6	20.1	36.2	34.6	37.5	.89
Sol Org P mg/m^3	5.3	8.8	7.3	7.5	7.0	7.5	7.3	15.3	14.3	12.8	.77
Part P mg/m^3	11.5	13.8	16.9	16.8	22.7	21.9	20.6	39.8	29.4	45.8	.92
Total P mg/m^3	22.5	29.1	32.2	38.4	41.3	46.5	40.6	75.1	61.1	83.3	.92
TN/TP	16.4	15.2	18.5	19.4	16.6	17.6	16.7	12.2	14.9	10.6	-.78
Inorg N/Sol P	7.9	9.9	12.6	12.6	16.0	15.6	15.8	18.2	15.2	11.9	.31
Alkalinity mg/l	0.2	9.4	15.1(31)	19.5(61)	19.6(54)	22.2(56)	21.3(82)	20.7(44)	21.9(54)	20.7(22)	.56
Cond µmhos/cm	52	186	71(30)	83(61)	89(64)	106(59)	92(92)	113(61)	107(59)	125(25)	.24
Cell Density	862	2851	1872	3082	4045	5648	4903	6236	5662	10[illegible]01	.93
Biovolume mm^3/m^3	937	2665	2259	1772	1507	2047	2250	2920	2419	4312	.81
Ln Cell Den	6.2211	7.2080	7.0761	7.2820	7.4359	7.4654	7.5052	7.7444	7.8578	8.6345	.90
Ln Biovol	6.2197	7.0604	6.8009	6.7693	6.6989	6.7622	6.8947	7.1062	7.1922	7.7809	.86
Chlor a mg/m^3	28	21(14)	22(36)	27(87)	29(95)	33(75)	30(164)	43	40	70	.94
Prod mg C/m^3/hr	15.6(5)	16.5(11)	14.8(19)	26.8(44)	31.2(48)	48.1(42)	48.3(79)	73.4(51)	68.1(46)	113.3(22)	.974
BI-B (x)	0.3	1.8	3.2	4.8	6.7	8.7	12.0	17.2	23.8	36.7	-

*If N deviates from values shown by more than 10% then actual N is in parenthesis.
**5% level of significance >.602
1% level of significance >.755.

Correlations - Trophic Indices and Mean Values of Associated Indices

Extending the limited comparison of Table 33, Secchi depth, chlorophyll a, total phosphorus, cell density, biovolume, Pollution Index and conductivity are compared in cross reference by their degree of correlation with the entire list of indices or other parameters of trophic state such as productivity (Table 35). It is clear from the patterns of both positive and negative correlation and the levels of significance, several of these water quality dimensions have consistent patterns of high correlation with either the direct or indirect determinants of the trophic state. These have been organized in Table 36. Their range of values encountered in this investigation is also shown. These levels establishe the range of effectiveness for North Carolina waters as trophic state indicators.

Although Secchi depth is not included in this examination of the cross relationships of the several indices, its relationship can be noted in Table 35. Its level of correlation is generally somewhat lower although above the level of 5% significance except in the case of total phosphorus. This low correlation was due to the lack of sensitivity of Secchi depth (mean values) to changes in higher phosphorus concentrations (see Table 9). Nevertheless in the final determination as to what has a practical application for rapid monitoring purposes as well as the effectiveness of the Secchi measurement, particularly in waters of low sediment content, three measures of trophic state were concluded as being best suited for North Carolina waters. These are shown in Table 37; total phosphorus in the range of <10 to >150 mg/m , conductivity from <19 to >200 μmhos per cm^2 and Secchi depth in the range of 0.1 to more than 3.0 meters. The range of quality values described in Table 37 defines for total phosphorus a slight shift to a higher range than was first suggested by Vollenweider (1968). However, this scale for North Carolina waters recognizes the local geological and cultural context as well as local water uses.

Trophic Classification

Six levels of trophic state have been defined for each of these indices as well as the probable relationship to water quality for contact water sports and fishing potential. Utilizing this scale of classification 69 bodies of water in North Carolina lakes, reservoirs or subsegments of large reservoirs have been classified (Table 38). Details of classification for each body of water are reported in Weiss and Kuenzler (1976). The relationship

Table 35

Correlation Coefficients (r) As Calculated Between Rank Series of Trophic Indices and Mean Values of Associated Indices Determined on the Same Sample*

	Secchi Depth	Chlorophyll a	Total Phosphorus	Cell Density	Biovolume	Poll. Index	Conductivity
Secchi-M	-	-.72	(-.53)	-.64	-.58	-.59	(-.63)
Chlorophyll *a* mg/m^3	-.85	-	.962	.963	.978	.989	.981
Total Phosphorus mg/m^3	-.72	.957	-	.92	.975	.991	.954
SD-TSI	-.92	.975	.57	.59	(.46)	.73	.72
CH-TSI	-.91	.91	.86	.79	.85	.80	.84
TP-TSI	-.81	.989	.80	.88	.82	.88	.90
Color PT Units	-.74	(-.14)	.37	-.64	-.56	(-.07)	(-.41)
Turb JTU	-.69	.88	.62	(.19)	(.23)	(.17)	(-.15)
Aut. Wgt	-.80	-	.962	(.14)	(-.19)	(.05)	.75
Filt. Wgt.	-.78	-	.93	(.02)	(-.20)	(.15)	.90
Cell Density no/ml	-.93	.965	.99	-	.81	.993	.974
Biovolume mm^3/m^3	-.81	.950	.964	.991	-	.991	.987
Shannon-Weaver Index	-.98	.74	(.38)	-.56	-.64	(.14)	.73
Evenness Index	(-.08)	(.35)	(.35)	-.78	-.87	(-.45)	.72
Pollution Index	-.91	.99	.967	.987	.963	-	.984
Taxa	-.82	.76	.72	.66	(.38)	.52	.75
BI-A	-.96	.90	.74	.54	(-.001)	(.36)	(.61)
BI-B	-.95	.88	.62	(.50)	(-.02)	(.26)	(.53)
BI-C	-.75	(.38)	(.04)	(-.30)	-.91	.64	(.37)
BI-D	-.84	.93	.78	(.45)	-.80	.61	(.57)
BI-E	-.92	.91	.81	(.26)	-.63	.77	(.54)
Productivity	-.87	.958	.94	.961	.962	.94	.94

( ) Below 5% level of significance.

* Comparison can be made along vertical series since (r) values are taken from the table of each given index.

Table 36

The Correlation of Total Phosphorus, Conductivity and Pollution Index As Trophic State Indices and Mean Values of Algal Growth Measures

Correlation Coefficients (r)

Independent Variable Stepped Rank Sets	Dependent Variables							
	Range	Total Phosphorus	Conductivity	Pollution Index	Cell Density	Bio-volume	Chlorophyll _a_	Average
Total Phosphorus	1-500 mg/m^3	-	.982	.967	.991	.964	.962	.973
Conductivity	30-500 μmhos/cm	.964	-	.978	.971	.989	.978	.976
Pollution Index	0-4000	.991	.914	-	.993	.991	.989	.976
Cell Density	150-70,000 units/ml	.916	.993	.987	-	.991	.963	.970
Biovolume	10-55,000 mm^3/m^3	.975	.833	.963	.980	-	.978	.946
Chlorophyll _a_	0.8-200 mg/m^3	.957	.996	.989	.965	.950	-	.971

Table 37

Range of Trophic Classification
Suggested for North Carolina Lakes

Total Phosphorus[1] mg/m^3	Conductivity[1] μmhos/cm^2	Secchi Depth[1,2] Meters	Trophic State	Expected Quality of Recreational Water Usage	
				Body Contact Water Sports	Probable Fishing Potential
<10	<19	>3.0	Oligotrophic	Excellent	Poor
10-19	20-49	1.5-3.0	Oligo-Mesotrophic	Excellent	Low
20-39	50-99	1.0-1.5	Mesotrophic	Good	Fair
40-79	100-150	0.5-1.0	α-Eutrophic	Fair	Good
80-150	150-199	0.1-0.5	β-Eutrophic	Poor	Excellent
>150	>200	<0.1	Hypereutrophic	Undesirable	Excellent[3]

[1] Each of these scales has been prepared independent of the others. They may be generally compared at each level but should not be directly equated.

[2] Simple to use but measurements made in waters with heavy sediment loads must be interpreted with care.

[3] Fish kills may occur because of low oxygen levels at night or following prolonged periods of cloud cover. This transition in fishing potential generally includes a species shift from those types considered game (oligotrophic waters) to coarse (eutrophic waters).

Table 38

Surface Waters of North Carolina and Immediate Adjacent Areas Sampled for Trophic State Analysis 1971-1975

Type and Name	Lake Codes: Map	Lake Codes: Computer	Trophic State - Summer Conditions: Oligotrophic	Oligo-mesotrophic	Mesotrophic	Eutrophic α	Eutrophic β	Hypereutrophic
Natural Lakes								
Black	1	BL				X		
Jones	2	JO		X				
Mattamuskeet	3	MA				X		
Phelps	4	PH			X			
Salters	5	SA		X				
Singletary	6	SL			X			
Waccamaw	7	WA			X			
White	8	WH		X				
Impoundments								
Cooling Water								
Belews	9	BC		X				
Hyco	10	HY			X			
Water Supply								
University	11	UN			X			
Michie	12	MC			X			
High Point	46	HP				X		
Wheeler	47	WE				X		
Brandt	48	BR				X		
Burlington	49	BU				X		
Lexington-Thomasville	50	LT					X	
Townsend	51	TO				X		
Hydroelectric and Flood Control								
Roanoke River								
John H. Kerr	28	KR						
Roanoke Arm								
Above 58-15 bridge					X			
Dam to Buoy 14				X				
Nutbush Arm								
Above 1308 bridge								X
Buoy N to 1308 bridge					X			
Buoy C to Buoy K				X				
Gaston	29	GA			X			
Roanoke Rapids	30	RR		X				

Table 38 (cont'd)

	Lake Codes		Trophic State - Summer Conditions					
Type and Name	Map	Computer	Oligotrophic	Oligo-mesotrophic	Mesotrophic	Eutrophic		Hypereutrophic
						α	β	
Yadkin River								
W. Kerr Scott	22	KS	----	X				
High Rock	23	HR	----	----	----	----	X	
Tuckerton	24	TU	----	----	----	X		
Badin	25	BA	----	----	X			
Tillery	26	TL	----	----	X			
Blewett Falls	27	BW	----	----	X			
Catawba River								
James	13	JA	----	X				
Rhodhiss	14	RH	----	----	X			
Hickory	15	HK	----	----	X			
Lookout Shoals	16	LS	----	----	X			
Norman	17	NR	----	X				
Mt. Island	18	MT	----	X				
Wylie (N.C.-S.C.)	19	WY	----	----	X			
South Fork	-	SF	----	----	----	X		
Fishing Creek (S.C.)	20	FC	----	----	----	X		
Wateree (S.C.)	21	WT	----	----	----	X		
Broad River								
Lure	61	LU	----	X				
Green River								
Adger	62	AD	----	X				
Summit	60	SM	----	X				
Toxaway River								
Toxaway	59	TX	---- X					
Hiwassee River								
Chatuge	56	CT	---- X					
Hiwassee	55	HW	---- X					
Nantahala River								
Nantahala	54	NA	---- X					
Cheoah River								
Santeetlah	53	SN	---- X					
Little Tennessee River								
Fontana	52	FO	---- X					
Highland	57	HL	----	----	X			
Tuckaseigee River								
Thorpe	58	TH	---- X					

Table 38 (cont'd)

Type and Name	Lake Codes		Trophic State - Summer Conditions					
	Map	Computer	Oligotrophic	Oligo-mesotrophic	Mesotrophic	Eutrophic α	Eutrophic β	Hypereutrophic
River Segment								
Chowan (U.S. 13 to Albemarle Sound)	44	CH				X		
Albemarle Sound		AL			X			
Roanoke River		RO			X			
Old Mill Ponds (year constructed)								
Crystal (1885)	31	CL				X		
Davies (1850)	32	DM				X		
Finches (1875)	33	FH				X		
Hodgins (1871)	34	HO			X			
Jackson (1885)	35	JK					X	
Johns (1840)	36	JH						X
Jones (1810)	37	JP				X		
Lytches (1870)	38	LY			X			
McKensie (1860)	39	MK		X				
McNeils (1870)	40	MN			X			
Monroe (1825)	41	MO	X					
Orton (1810)	42	OR			X			
Tull (1875)	43	TM				X		
Silver (1785)	45	SI			X			

of the trophic state of these lakes and their surface area is shown in Table 39. The mean depth of 41 of the lakes when related to trophic state (scaled on a digital basis using values of 1-6) are correlated at an (r) of -.934 with a 1% level of significance >.834, Table 40. It would appear to follow from this relationship that the deep lakes, (in North Carolina all deep lakes are impoundments) have a much greater capacity for assimilation of nutrients. Substances that increase nutrient levels will tend to sink below the euphotic zone and are removed from significant re-entry into trophogenic levels. In the North Carolina context lakes shallower than a mean depth of 15-20 ft. would probably be not very responsive to quality upgrading. Nutrients from non-point sources are readily available for enhancement of productivity levels.

Table 39

Summary of Trophic Classifications
of North Carolina Lakes and Impoundments*

	Trophic Classification					
Surface Area - Acres	Oligo-trophic	Oligo-meso-trophic	Meso-trophic	α-Eutrophic	β-Eutrophic	Hyper-eutrophic
<500	1	6	6	6	1	2
500-1000	1	0	4	3	1	0
1000-5000	3	7	6	5	0	0
5000-10000	2	1	1	0	0	0
>10000	1	2	3	2	1	0
Physiographic Distribution						
Coastal Plain	1	5	7	7	0	1
Piedmont	0	8	12	9	3	1
Mountain	7	3	1	0	0	0

*Number identifies either the classification of an entire lake or impoundment or a subsegment if data was in sufficient detail.

Table 40

Relationship of Trophic State and Mean Depth
41 Lakes or Impoundments of North Carolina

Mean Depth- Feet $\left(\frac{\text{Volume}}{\text{Surface Area}}\right)$			Trophic State (Scaled 1-6)*		
N	Range	Mean	N	Range	Mean
6	4.9-8.4	6.8	6	3-6	4.0
7	9.4-13.5	11.8	7	2-4	3.3
6	15.8-18.8	17.1	6	2-5	3.3
8	20.5-26.7	23.4	8	2-4	3.0
6	31.0-38.4	34.5	6	1-3	2.3
5	40.7-55.2	48.1	5	1-2	1.6
3	69.7-135.4	97.1	3	1	1.0

Corr. Coef. r = -.934

slope 3.727

intercept -.031

d.f. = 6; 5% level of sig. >.707

1% level of sig. >.834

*1 - Oligotrophic
2 - Oligo-mesotrophic
3 - Mesotrophic
4 - α-Eutrophic
5 - β-Eutrophic
6 - Hypereutrophic

ACKNOWLEDGEMENTS

This investigation is based on data assembled in the period 1971-1975 and reflects the efforts of many individuals who participated in the collection and assessment of the quality of the hundreds of water samples. This information constitutes the data pool of this document. Responsibility for nearly all of the field work should be identified with Mr. Terry P. Anderson and Mark Mason. Mr. Anderson's comments, suggestions and review of drafts have been particularly helpful and should be specifically acknowledged. Christopher F. Knud-Hansen had the primary responsibility for the collection samples from the mill ponds and western lakes. Laboratory analyses, particularly the algal nutrients, were carried out under the supervision of Ms. Susan Rappaport and Ms. Carol Parker. All of the phytoplankton analyses were made by Dr. Peter H. Campbell. Coding and checking of the data for computer processing was the responsibility of Ms. Ann Scott. The typing of the numerous tables was a task carried out with great patience by Mrs. Elizabeth Walter.

Over the period of time in which the hundreds of observations of this report were gathered, there were several organizations and their specific projects which contributed directly or indirectly to the total data base. A principal source of data was the project, The Trophic State of North Carolina Lakes, supported by the Water Resources Research Institute of the University of North Carolina. However, the data base both preceded and postdates the period of support of this specific study. Other organizations and their projects that contributed by the data pool should be acknowledged as follows. U.S. Army Corps of Engineers, Wilmington District, The John H. Kerr Reservoir; Duke Power Company, the Lower Catawba Lakes and Belews Lake; the North Carolina Science and Technology Committee, Taxonomy and Ecology of the Phytoplankton of North Carolina.

The Central Computing and Data Processing Center, School of Public Health, under the direction of Mr. Robert Middour should be particularly acknowledged for their help in carrying out the innumerable data processing runs necessary for assembly of the key information used in assessing the relationships of the trophic indices to trophic conditions.

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A REVIEW OF TROPHIC STATE INDICES
FOR NEW YORK STATE

William R. Schaffner
and
Ray T. Oglesby

Department of Natural Resources
New York State College of Agriculture and Life Sciences
Cornell University
Ithaca, New York

INTRODUCTION

Since the early 1950's a number of attempts have been made to develop simple lake trophic state indices that could be related to such parameters as phytoplankton standing crop, quantity of benthos, and fish production. Mean depth was one of the first factors to be examined, with research being concerned with its influence on faunal production, especially that of fish (Rawson, 1952, 1955, 1960; Northcote and Larkin, 1956; Hayes, 1957). In some instances close correlations were obtained with discrete groups of lakes, but in general, "...the only generalization which seemed justified was that quantities of fauna from lakes of great mean depth were never as high as those in some lakes of low mean depth" (Northcote and Larkin, 1956). Sakamoto (1966) obtained a negative correlation between phytoplankton standing crop (log of the chlorophyll concentration) and log mean depth for a group of Japanese lakes that ranged from 1 to 65 meters in mean depth. Vollenweider (1968) also argued that mean depth was an important trophic parameter and included it in his phosphorus-loading trophic state plots.

The influence of edaphic factors, as represented by total dissolved solids (TDS) or conductivity, has also been examined. Rawson (1951, 1960) and Northcote and Larkin (1956) examined lakes in central Canada and British Columbia, respectively, and observed that the production of net plankton, benthos and fish increased with increasing TDS, although there was considerable scatter except for those lakes with very low dissolved solids levels.

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Hayes and Anthony (1964) developed an index of fish productivity from multiple regressions that included alkalinity (roughly proportional to TDS or conductivity) as one of the variables. Earlier, Ball (1945) had found no significant correlation between alkalinity and fish abundance in thirty-two Michigan lakes.

Ryder (1961, 1965) formulated the morphedaphic index (MEI) as a means of estimating fish production, basing the index on the relationships developed by Rawson (1956) and Northcote and Larkin (1965). The MEI contains an edaphic variable (TDS or conductivity) and a morphometric variable (mean depth), and is expressed as the ratio of TDS (or conductivity) to mean depth. Although initially used to estimate fish production the MEI has more recently been related, with moderate success, to trophic conditions of various lakes (Harvey and Fry, 1973; Henderson et al., 1973; Michalski et al., 1973).

Vollenweider (1968) discussed in some detail the importance of nutrient input to lakes and its effect on lake trophic state, pointing out that lake morphometry should be taken into account when different lakes are being compared. This was accomplished by calculating nutrient loading on an areal basis, and plotting this versus mean depth. A graphic representation resulted which devided the lakes roughly into oligotrophic, mesotrophic and eutrophic categories. Subsequently, the influence of lake hydrology as well as morphometry was considered (Vollenweider and Dillon, 1974; Dillon, 1975; Dillon and Rigler, 1974).

Hydraulic retention time (HRT) has been related to lake productivity, but the actual point at which it becomes a significant factor is not well defined, although, some indications do exist. Dickman (1969) found evidence that HRT could be of significance to some lakes in his study of a small British Columbia lake that flushed as often as every 2.5 days during periods of heavy rainfall. Kerekes (1973, 1975b) noted in his studies of Newfoundland and Nova Scotian lakes that at HRT's <0.2-0.4, chlorophyll and total phosphorus concentrations became a function of the flushing rate. Similarly, Dillon (1975) found that the phytoplankton standing crop in a rapidly flushed Ontario lake (HRT <0.1 yr) was lower than expected based on phosphorus loading data. Vollenweider (1975) has provided a theoretical basis for the influence of HRT on lake productivity, and later versions of his phosphorus loading-mean depth-trophic state graph have been modified to include HRT (Vollenweider and Dillon, 1974).

Recently, Carlson (1975) presented a system for the trophic classification of lakes using indices based on single parameters (Secchi disc transparency, chlorophyll a and total phosphorus) known to be closely affected by changes in trophic state. The different trophic states are derived for a given index by division of the range of values obtained for the index parameter. For example, Secchi disc transparency (SDT) can be related to algal biomass by using the Beer-Lambert equation for the vertical extinction of light in water. Based on this fact SDT is used to delineate the desired trophic categories such that each division represents a doubling in the concentration of algal biomass in the surface waters, where biomass is defined in terms of transparency. The zero point for the index was chosen at an SDT value greater than any yet recorded in the literature - 64 meters. A maximum of 41.6 meters was reported in Hutchinson (1957) for Lake Masyuko, Japan. The total trophic scale ranges from 0 to 100, with major divisions as follows: 64m = 0; 32m = 10; 16m = 20; ...; 0.062m = 100.

The present report describes the results obtained when the various trophic state indiced are applied to a relatively diverse group of New York State lakes.

MATERIALS AND METHODS

Data were obtained for twenty-seven New York lakes, although it was not possible to obtain a complete set of parameters for each. They are located throughout most of the state, Long Island excepted, and occur in a variety of geological settings (Table 1). Oneida, the largest, receives runoff from three physiographic provinces: the Appalachian Upland, Erie-Ontario Lowland and Tug Hill Upland (Greeson, 1971). One of the lakes (Moraine) is man-made; the rest occur naturally.

The data came from a number of sources, published and unpublished; as a result some of the parameters are not always exactly comparable. In some instances it was necessary to substitute median values for means. Such modifications are not thought to greatly affect the outcome of the study. The additional information outweighing any introduced variability.

Table 1. A list of the twenty-seven New York lakes catagorized as to the physiographic provinces in which their basins are located. A brief description of each physiographic province can be found in Table 2.

Adirondack Highlands

- Carry Falls Reservoir
- George
- Lower St. Regis
- Mirror
- Placid
- Sacandaga
- Schroon
- Upper Saranac

Appalachian Uplands

- Canadarago
- Canadice
- Canandaigua
- Cayuga
- Chautaugua
- Conesus
- Hemlock
- Honeoye
- Keuka
- Lamoka
- Moraine
- Otisco
- Otsego
- Seneca
- Skaneateles
- Waneta

Erie-Ontario Lowlands

- Oneida

Hudson-Mohawk Lowlands

- Saratoga

Table 2. A brief description of five of New York's physiographic provinces (Cressey, 1966; Greeson, 1971).

Adirondack Highlands	Ancient crystalline rocks, similar to those of the Canadian Shield, prevail. Intense glacial scouring has removed most of the original soil and smoothed out the land surface. Some of the erroded material now chokes the pre-glacial valleys, deranging the stream patterns and producing numerous lakes.
Appalachian Uplands	The largest land form in New York, occupying nearly half of the state. Underlain by Paleozoic sedementary rocks. Upper Devonian sandstones and shales are found in the southern portion, changing to Middle Devonian limestones northward.
Erie-Ontario Lowlands	A relatively flat region bordering Lake Ontario. The bedrock is composed of shale, limestone and minor amounts of sandstone, which may be overlain by up to 30 meters of unconsolidated glacial deposits.
Hudson-Mohawk Lowlands	The soft sedimentary rocks and overlying glacial deposits have been erroded to form a variety of terrain. The region north of Albany is wide and flat, and is covered with glacial deposits. Unusual carbonated, saline waters are found in the Saratoga-Ballston Spa district.
Tug Hill Uplands	A plateau-like outlier of the Adirondack Highlands underlain by Paleozoic sandstones, limestones and shales which dip gently westward. An area of bad drainage, poor soils and heavy snows, it is one of the least settled parts of the state.

Data for a given lake during different years are not pooled, but reported separately so as to provide some estimate as to the natural variability within a lake.

Phosphorus loading are in g total P/m^2 lake surface/year. The other parameters are defined in the appropriate tables. Carlson's trophic state indices (TSI) were calculated from the following formulas:

(1) Summer Secchi disc transparency

$$TSI(SD) = 10\ (6 - \frac{\ln SD}{\ln 2})$$

(2) Summer chlorophyll a (surface)

$$TSI(Ch) = 10\ (6 - \frac{2.04-0.68 \ln Ch}{\ln 2})$$

(3) Summer total phosphorus (surface)

$$TSI(TP) = 10\ (6 - \frac{\ln \frac{64.9}{TP}}{\ln 2}).$$

The calculation of MEI was discussed in the previous section. Total alkalinity concentrations were reported in standard fashion.

RESULTS

Morphology and Hydrology

Morphometric and hydroligic parameters for the twenty-seven New York lakes are summarized in Table 3. The locations of the lakes are also listed. The lakes represent a relatively wide

Table 3. Morphometric and hydrologic data, and location of the twenty-seven New York lakes. Data from Greeson and Robison (1970), and Oblesby and Schaffner (1975).

Lake	Location N. Lat °	'	"	W. Long °	'	"	Surf Elev. m	Surf Area km²	Drain Area km²	Depth m max	mean	Vol. km³	WRT yrs	$\bar{z}/\tau$
1 Canadarago	42	47	24	75	00	51	389	7.6	174	12.8	6.7	0.05	0.6	11.2
2 Canadice	42	44	27	77	34	20	334	2.6	31	25.4	16.4	0.04	4.5	3.6
3 Canandaigua	45	52	30	77	16	20	210	42.3	453	38.5	38.8	1.6	7.4	5.2
4 Carry Falls Res	44	25	55	74	45	10		26.1	2261		5.4	0.14	0.1	54.0
5 Cayuga	42	56	51	76	44	09	116	172.1	2106	132.6	54.5	9.4	12.0	4.5
6 Chautaugua	42	06	43	79	06	08	399	57.2	490		6.9	0.40	1.4	4.9
7 Conesus	42	50	04	77	42	18	249	13.7	231	18.0	11.5	0.16	1.4	8.2
8 George	43	50	13	73	25	50	97	114.0	492	57	18	2.1		
9 Hemlock	42	46	39	77	36	59	276	7.2	111	27.5	13.6	0.11	2.0	6.8
10 Honeoye	42	47	00	77	30	42	245	7.0	95	9.2	4.9	0.04	0.8	6.1
11 Keuka	42	39	22	77	03	40	245	47.0	484	55.8	30.5	1.4	6.3	4.8
12 Lamoka	42	24	59	77	05	10	335	2.3	18	14.3	5.0	0.01		
13 Lower St Regis	44	25	52	74	17	53	494	1.9	54.9		5.1	0.01	0.3	17.0
14 Mirror	44	17	02	73	58	56	566	0.5						
15 Moraine	42	50	47	75	31	39	369	1.1						
16 Oneida	43	14	20	76	08	30	113	206.7	3579	16.8	6.8	14.0	0.6	11.3
17 Otisco	42	54	16	76	18	47	240	7.6	88	20.1	10.2	0.08	1.9	5.4
18 Otsego	42	41	40	74	55	18	363	16.6	75	51.0	12.6	0.21		
19 Owasco	42	54	12	76	32	34	217	26.7	539	54.0	29.3	0.78	3.1	9.4
20 Placid	44	18	16	73	59	43	567	11.3	52					
21 Sacandaga	43	19	10	73	55	26	235	122.0	2704		7.6	0.93	0.5	15.2
22 Saratoga	43	06	10	73	38	12	62	16.3	632		7.9	0.13	0.4	19.8
23 Schroon	43	43	40	73	48	42	246	16.7	1189		14.3	0.24	0.4	35.8
24 Seneca	42	52	06	76	56	26	136	175.4	1831	198.4	88.6	15.5	18.1	4.9
25 Skaneateles	42	56	42	76	25	47	263	35.9	189	90.5	43.5	1.6	17.7	2.5
26 Upper Saranac	44	15	04	74	17	48	480							
27 Waneta	42	27	56	77	06	17	335	3.2	46	8.8	3.5	0.01		

range of differences. Saratoga is the lowest with a surface altitude of 62 meters, and Placid is the highest at 567 meters. Mirror Lake has a surface area of only 0.5 km^2; whereas Oneida, the state's largest lake, has an area of 206.7 km^2. As one might expect, drainage areas also vary considerably. Lamoka's is 18 km^2 while Oneida has a drainage area covering 3579 km^2. Three other lakes (Carry Falls Reservoir, Cayuga and Sacandaga) have basins in excess of 2000 km^2. Volumes differ by over four orders of magnitude, and mean depths two, from 3.5 meters (Waneta) to 88.6 meters in Seneca, the state's deepest lake. Some of the lakes are flushed quite rapidly, Carry Falls Reservoir has a mean hydraulic retention time of 0.1 yrs, and seven others (Canadarago, Honeoye, Lower St. Regis, Oneida, Sacandaga, Saratoga and Schroon) flush on the average in less than a year. Seneca and Skaneateles have mean HRT's on the order of twenty years.

Trophic State Indices

Six trophic state indices plus supportive data are listed in Table 4.

Carlson's Indices: The first three indices are those of Carlson (1975), which are based on the single parameters: Secchi disc transparency, surface chlorophyll *a* and surface total phosphorus. These indices are represented on a scale of 0 to 100, with the most oligotrophic category having a value of zero.

Secchi disc transparencies varied from 1.2 to 9.3 meters. The index, TSI(SD), ranges from 28 (George) to 57 (Lower St. Regis). Most values are in the 30's, 40's, and 50's (Figure 1).

Table 4. Trophic state indices and supportive data for the twenty-seven New York lakes.

Lake	Year	SDT m	TSI (SD)	Chl mg/m^3	TSI (Ch)	TP mg/m^3	TSI (TP)	TDS mg/l	MEI (TDS)	Cond. µmhos/cm	MEI (Cond)	T. Alk. mg CaCO$_3$/l	L_{sp} g P/m^2/yr
1 Canadarago	1973			3.2	42			174	26	279	42	137	1.2, 0.79[3]
2 Canadice	1973	5.2	36	2.0	37	10.2	33	76	5	115	7	32	0.32, 0.36[5]
3 Canandaigua	1972	4.5	38	4.3	45	9.0	31			310	8	111	
	1973	3.9	40	3.0	41	9.2	32	187	5	285	7	108	0.42, 0.14[8]
4 Carry Falls Res	1972	2.3	48	3.1	42	10.0	33			50	9	10	0.71[7]
5 Cayuga	1965[10]	2.4	47	6.4	49	18.3							
	1968	2.6	46	6.2	48							105	
	1972	1.8	52	11.5	54					500	9	110	0.86, 0.81[1], 0.49[7]
	1973	2.3	48	6.8	49	14.6	38	213	4	485	9	113	
	1974	2.3	48	9.5	53	31.4	49						
6 Chautauqua	1972	2.0	50	13.3	56	28.0	48			150	22	49	0.27[8]
7 Conesus	1971	4.5	38	5.8	48								
	1972	4.7	38	4.2	45	18.3	42			340[8]	30	116[8]	0.67, 1.4[4], 0.38[6]
	1973	5.2	36	3.7	43	11.3	35	209	18	328	29	114	
8 George[11]		9.3	28										
9 Hemlock	1971	4.3	39	5.4	47			136	10				
	1972	2.7	46	7.6	50	10.6	34						0.43
	1973	3.0	44	5.0	46	9.2	32			193	14	59	
10 Honeoye	1973	3.0	44	25.7	62	19.0	42	119	24	166	34	62	0.38, 0.83[6]

Table 4. Continued

11 Keuka	1972[1]	2.4	47	8.0	51	13.0	37	165	5	241[8]	8	92	0.45, 0.10[9]
	1973	7.0	32	1.8	36	14.2	38			276	9	76	
12 Lamoka	1973	2.0	50	8.7	52	12.0	36	100	20	150	30	54	
13 Lower St. Regis	1972	1.2	57	7.9	51	17.0	41			50	10	10	0.41[11]
14 Mirror	1971	4.8	37	14.1	56							9	
15 Moraine	1974	3.2	4	7.4	50	20.3	43						
	1975	5.8	35	4.4	45								
16 Oneida	1965[12]							176	26	278	41		
	1967[2]	1.9	51			36.0	52	163	24	290	43	81	
	1968[2]	1.9	51			41.0	53			250	37		0.87, 1.3[2]
	1973			8.5	52	68.4	61	194	29	302	44	117	
	1975[13]	2.7	46	17.1	58	39.1	53						
17 Otisco	1965[12]							194	19	287	28		
	1973	5.2	36	1.8	36	9.6	32	183	18	293	29	133	0.55
18 Otsego													
	1973	3.0	44	1.8	36	7.1	28	160	13	238	19	101	
19 Owasco	1965[12]							160	6	263	9		
	1971	3.8	41	6.6	49								
	1972	3.1	44	5.0	46	17.5	41			280[8]	10	107[8]	0.97
	1973	2.5	47	4.9	46	9.9	33	167	6	262	9	113	
20 Placid	1971	9.5	28	1.3	33							8	
21 Sacandaga	1972	3.5	42	4.8	46	9.0	31			50	7	10	0.18[1]
22 Saratoga	1972	2.5	47	11.8	55	25.0	46			232	29	72	1.6[8]
23 Schroon	1972	3.7	41	2.1	38	4.0	20			59	4	10	0.39[1]

Table 4. Continued

24 Seneca	1965[10]	3.1	44	4.8	46	22.0							
	1972	1.8	52	13.0	56	15.0	39			790[8]	9	92	0.64, 0.38[5]
	1973	3.6	42	8.6	52	10.2	33	276	3	769	9	90	
25 Skaneateles	1965[12]							142	3	224	5		
	1971	7.9	30	1.1	32								
	1972	6.6	33	2.6	40	28.5	48						0.23
	1973	5.2	36	1.3	33	6.1	26	144	3	275	6	98	
26 Upper Saranac	1971[14]	3.5	42			26.0	47						
27 Waneta	1973	1.5	54	23.6	62	23.8	46	113	32	152	43	52	

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[1] Likens (1974); Oglesby (MS 1974)

[2] Greeson (1971)

[3] Hetling and Sykes (1971)

[4] Anonymous (1974a)

[5] Anonymous (1974b)

[6] Stewart and Markello (1974)

[7] Hetling (1974)

[8] Anonymous (1975)

[9] Anonymous (1974c)

[10] Anonymous (1966)

[11] Hetling (1974)

[12] Shampine (1973)

[13] Dr. E. L. Mills (personal communication)

[14] Anonymous (1972)

Cayuga was sampled during five different years for the period 1965-74, and its index values range from 46 to 52.

Chlorophyll concentrations varied from 1.1-25.7 mg/m^3; TSI (Ch) values are distributed in a fashion similar to those of TSI(SD) (Figure 1). Skaneateles (1971) has the lowest index (32), but data were not available for Lake George. Waneta and Honeoye are the highest at 62. Most of the indices are in the 30-60 range. Cayuga varies from 46 to 52. Skaneateles was 32 in 1971, 40 in 1972, and down to 33 in 1973. Seneca had an index of 46 in 1965 and 56 in 1972.

Total phosphorus concentrations range 6.1 mg P/m^3 in Skaneateles (1973) to 68.4 mg P/m^3 in Oneida (1973). The total P index, TSI(TP), has the greatest span, from 20 (Schroon) to 61 (Oneida-1973). Approximately 75% of the values are in the 30's and 40's (Figure 1). Oneida varied from 52 in 1967 to 61 in 1973, while Skaneateles went from 48 in 1972 down to 26 in 1973.

Morphoedaphic Index. The MEI's were calculated with total dissolved solids (TDS) and conductivity. TDS concentrations range from 76 mg/l in Canadice to 276 mg/l in Seneca, and the resulting MEI's from 3 (Skaneateles and Seneca) to 32 (Waneta). Five lakes (Canadarago, Honeoye, Lamoka, Oneida and Waneta) are 20 or greater, and eight (Canadice, Canandaigua, Cayuga, Hemlock, Keuka, Owasco, Seneca and Skaneateles) are 10 or less.

Conductivity ranges from 50 micromhos/cm^2 in Lower St. Regis and Sacandaga to 790 micromhos/cm^2 in Seneca. The MEI's vary from 4 (Schroon) to 44 (Oneida). Three lakes (Canadarago, Oneida and

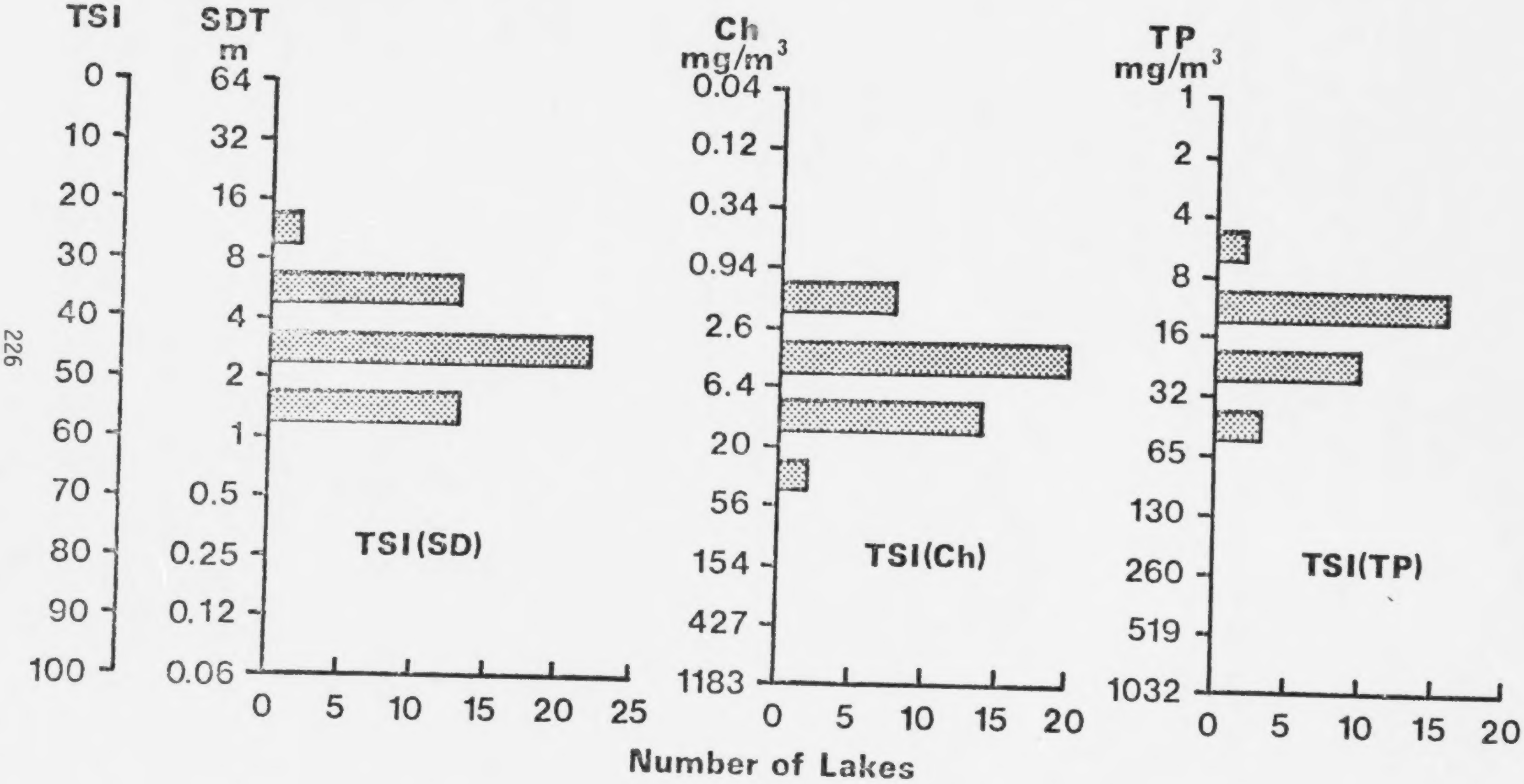

Figure 1. Frequency distribution of Carlson's Trophic State Indices.

Waneta) are in the 40's, while ten (Canadice, Canandaigua, Carry Falls, Cayuga, Keuka, Owasco, Sacandaga, Seneca and Skaneateles) are 10 or less.

Specific Phosphorus Loading. L_{sp} estimates for a specific lake may vary considerably when calculated by different researchers, e.g. the three estimates for Conesus range from 0.38 to 1.4 g $P/m^2/yr$. Skaneateles has the lowest loading (0.23 g $P/m^2/yr$) and Saratoga the highest (1.7 g $P/m^2/yr$). Three other lakes (Canadarago, Conesus and Oneida) have at least one estimate greater than 1.0 g $P/m^2/yr$. The phosphorus loading to the various lakes are plotted on Vollenweider's revised graph which utilizes mean depth/HRT on the x-axis (Figure 2). The majority of the lakes fall in the "eutrophic" classification. Three (Chautaugua, Lower St. Regis and Skaneateles) are classified as "mesotrophic", i.e. they lie between the permissible and dangerous loading limits, and three (Carry Falls, Sacandaga and Schroon) fall into the oligotrophic category. Two (Canandaigua and Keuka) were ranked as being both oligotrophic and eutrophic.

Correlations Between Trophic State Indices

Excepting that between the two MEI's, correlations between the various indices are not high (Table 5). Three combinations: TSI(SD) vs TSI(Ch), TSI(TP) vs MEI(TDS) and TSI(TP) vs MEI(Cond), had R values around 0.7, all others were less.

Alkalinity

Total alkalinities are presented for information only, and no attempt has been made to make trophic interpretations from them.

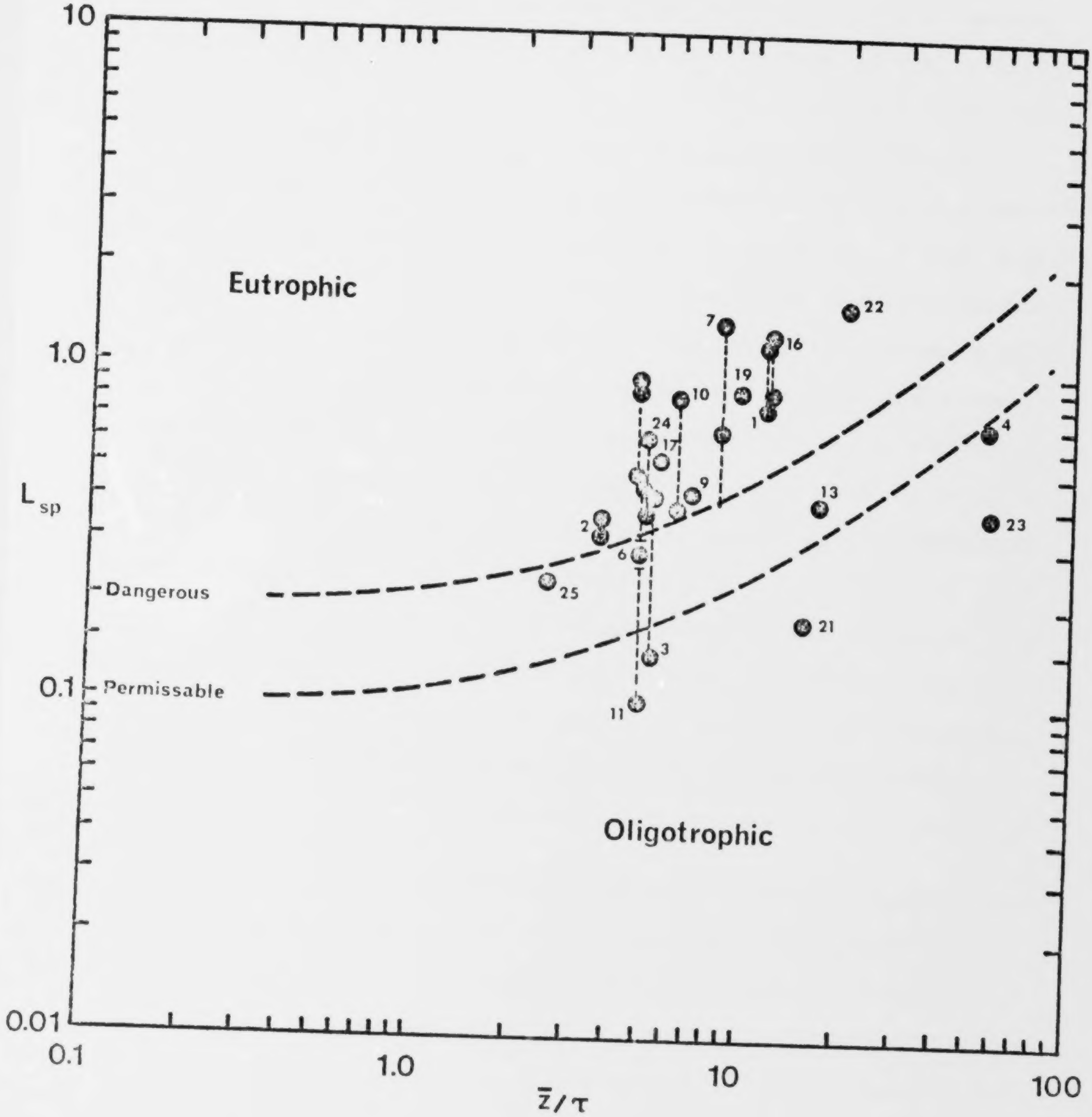

Figure 2. Specific phosphorus loadings to nineteen New York lakes. Estimates for the same lake are connected by a dashed line. Lakes identified by number, see Table 3 or 4 for identification.

Table 5. Correlation coefficients (R) for TSI and MEI values.

	TSI(SD)	TSI(Ch)	TSI(TP)	MEI(TDS)	MEI(Cond)
TSI(SD)	-	0.707	0.406	0.447	0.274
TSI(Ch)		-	0.525	0.459	0.387
TSI(TP)			-	0.725	0.688
MEI(TDS)				-	0.988
MEI(Cond)					-

Alkalinity ranges from 8 mg $CaCO_3$/l in Lake Placid to 137 mg $CaCO_3$/l in Canadarago. Lakes located in the Adirondack Mountains (Carry Falls, Lower St. Regis, Mirror, Placid, Sacandaga and Schroon) had alkalinities that were considerably lower than those lakes located in other parts of the state, i.e. the former had alkalinities of about 10 mg $CaCO_3$/l, whereas the latter did not have concentrations that went below 49 mg $CaCO_3$/l.

DISCUSSION

Various trophic state indices and indicators were applied to a diverse group of New York lakes using both published and unpublished data from a number of sources.

Total alkalinities are reported where available, and differ widely in various areas of the state. The differences are more closely related to edaphic factors than lake trophic state. The soft waters of the Adirondack lakes have alkalinities of 10 mg $CaCO_3$/l or less, whereas those in the Finger Lakes region can have concentrations of 100 mg $CaCO_3$/l, or better, due to the presence of limestone in their drainage basins.

The MEI's calculated from TDS and conductivity suffer from the same problem as the alkalinity estimates. This is compounded by the fact that two of the lakes (Cayuga and Seneca) have elevated sodium chloride levels (Oglesby et al., 1974), although the great mean depths of the lakes tend to mask the problem when MEI's are calculated. The reason for the relatively good correlation between TSI(TP) and the two MEI's remains obscure, although one could argue that phosphorus concentrations in the water are more closely related to morphoedaphic parameters than either transparency or chlorophyll. The problem warrents closer examination.

The trophic state indices proposed by Carlson (1975) probably represent the most practical approach when a large number of lakes are being studied and their trophic status followed over a number of years, even though there was a lack of strong correlation between the indices when they were applied to the New York lakes (Table 5). The necessary data can be gathered with reasonable ease since each index is based on a single parameter. Secchi disc transparency, surface chlorophyll a and surface total phosphorus, each of which is related to lake trophic state, should reflect any changes that take place.

The New York lakes fall in the mid-range of Carlson's (1975) trophic index scale, the maximum range being from 20 to 61. All of the mean Secchi disc transparencies are between 1 and 10 meters. Mean surface chlorophyll concentrations do not go below 1 mg/m^3, with a high of 25 mg/m^3 being observed in Honeoye. The next two highest chlorophyll concentrations are from Mirror and Chautaugua, about 14 and 13 mg/m^3. Transparencies in the three lakes are not as low as one might expect, at 3.0, 4.8 and 2.0 meters respectively.

Total phosphorus concentrations range over an order of magnitude, i.e. from 6 to 68 mg P/m^3. The greatest difference for a single lake may be found in Skaneateles which went from 28.5 mg P/m^3 in 1972 to 6.1 mg P/m^3 in 1973. Heavy rains associated with Tropical Storm Agnes fell on the state in 1972, a factor that could have influenced lake phosphorus concentrations. Examination of Table 2 shows that some of the lakes followed a pattern similar to Skaneateles, but to a much lesser extent. Chlorophyll levels in Skaneateles were greater in 1972 than 1973 (2.6 vs 1.3 mg/m^3), as was transparency (6.6 vs 5.2 m).

The lack of a strong correlation between the three TSI's is perplexing, but may be explained at least in part by several factors. The data that were used came from a variety of sources. In some instances the lakes were sampled on almost a weekly basis during the summer, in others only two or three samplings were conducted. Thus, some of the lakes may not have been adequately characterized. The data were not truely comparable in all instances, e.g. median values were at times substituted for means. In addition, the various lakes may have responded differently for each of the three parameters, e.g. the phosphorus values from Skaneateles, and the chlorophyll-transparency relationships in Honeoye, Mirror and Chautaugua that have already been mentioned.

Long-term data for the various parameters were not available, thus it was not possible to trace changes that may have taken place in trophic state. Carlson (1975) was able to do this with information from Lake Washington, and demonstrated that the indices performed adequately. Variations of from 10 to 20 units were noted in the New York lakes over periods of only a few years; this may represent the natural range to be expected.

Specific phosphorus loading (L_{sp}) estimates were available for nineteen of the lakes. In some instances where more than one estimate was made for a particular lake, considerable range was encountered, e.g. the three values for Conesus vary by more than a factor of three (Table 2). This was most likely due to the way in which the loading estimates were obtained, and is not thought to represent actual differences. Stewart and Markello (1974), and Oglesby and Schaffner (1975) calculated their phosphorus loadings based on such factors as land use and population size in the drainage basins, but made different assumptions as to relative contributions from each. The estimates presented in Anonymous (1974a, 1974b, 1974c and 1975) were based on stream and sewage treatment plant measurements. This usually did not affect the ultimate classification of a lake when the data were plotted (Figure 2), just its relative position on the graph. Two exceptions were Canandaigua and Keuka which were indicated as being both eutrophic and oligotrophic.

The majority of the lakes are classified as eutrophic when L_{sp} was plotted against $\bar{z}/\tau$ (Figure 2). Three (Carry Falls, Sacandaga and Schroon) are classified as oligotrophic, and fall into this category by virtue of their short HRT's (0.1-0.5 yrs) (Table 3). Examination of their other trophic state parameters, i.e. transparency, chlorophyll and total phosphorus (Table 4), would tend to place them somewhat higher on the trophic scale. Skaneateles, classified as mesotrophic, is quite transparent (Secchi disc: 5.2-7.9m), and has low chlorophyll levels (1.1-2.6

mg/m^3), but has a long HRT (18 yrs). Canandaigua and Keuka should possibly be classified as mesotrophic, although the latter differed considerably in 1972 and 1973 (Table 4).

If phosphorus loading estimates are to be used for management purposes they must be quantitatively accurate, or at least consistent. In addition, they should be related to measurable trophic state parameters, such as transparency, chlorophyll or total phosphorus, rather than to subjective terms such as eutrophic and oligotrophic which in fact represent a whole continuum of trophic levels. A preliminary attempt at rectifying some of the inherent problems is discussed in Oglesby and Schaffner (1975).

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